Final Report

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FAMILY OF COMPACTION CURVES FOR CHEMICALLY MODIFIED SOILS

by

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Family of Compaction Curves for Chemically Modified Soils

Introduction

Subgrades should be adequate in terms of strength and bearing capacity to ensure long term performance. Field conditions are not always favorable for compacting subgrade soils so as to achieve the desired strength and deformation properties which can be sustained over the pavement life. The soil in the field can be too wet to be workable or compactable. The presence of expansive clay minerals like smectite, which shrink upon drying and swell upon wetting, during significant wetting and drying periods, may tend to produce significant differential movements and lead to the failure of the entire pavement system. Chemical stabilization is employed in such situations to facilitate the construction of pavements, enhance the engineering properties of the soils, and ensure long term performance. Lime kiln dust (LKD) has been used in the state of Indiana as a subgrade modifier for a number of years.

Quality control and quality assurance of any subgrade is necessary to ensure long-term performance of the pavements. For a natural subgrade without modification by chemical additives, quality control consists of meeting moisture content and dry unit weight requirements. Maximum dry unit weight and optimum moisture content are two important parameters to characterize compaction. Moisture-unit weight relationships of chemically modified soils are different from natural soils and also change with

time (due to hydration) and environmental conditions. Therefore, moisture content and unit weight requirements are indirect indicators of various characteristics of a subgrade and might not be sufficient for quality control of stabilized subgrades.

The family of curves currently used by INDOT is developed for natural subgrades without chemical modification. There is need for a family of curves or other practical procedures for chemically modified soils that could be used to guide compaction and facilitate quality control.

The characteristics of a chemically stabilized subgrade are dependent on type and amount of stabilizer, the nature of clay minerals in the soil, the percentage of fines in the soil, temperature during and after mixing, thoroughness of mixing, delay time between mixing and compaction, availability of water, and type and energy of compaction. Therefore, a quality control procedure developed should consider all these factors and be a direct measure of the various properties of the subgrade.

The primary aim of this research project was to identify the various possible quality control procedures for chemically stabilized subgrades. Attempts were made to take the past research on chemically modified soils a step further by testing the potential of the Time Domain Reflectometry (TDR) method as a possible quality control method for modified subgrades.

Findings

The specific objectives of this research project were to: 1) To characterize LKD as a chemical stabilizer by identifying its chemical composition; 2) Understand the process of stabilization as performed in field; 3) Test the feasibility of using the current natural subgrade quality control method (a one-point test on a family of curves) for

chemically modified soils; 4) Automate the generation of a family of compaction curves and a one-point test interpolation; 5) Study the behavior of LKD modified soils in terms of their Atterberg limits, compaction characteristics; and 6) Study the electrical properties of LKD modified soils to develop a quality control method.

The major findings of this project were: 1) An automated method to generate Family of Compaction Curves in the form of a program FAMCURVES with a user-friendly interface on a Microsoft Excel platform; 2) The chemical composition of both sources of LKD used in the project, as identified by X-ray diffraction tests, justified their use for chemical modification of subgrades; 3) From the observations made during the field trips, the methods of mixing and compaction in field, although efficient, do not provide a uniform modified material throughout the depth and area of the modified subgrade, which makes simulating field conditions in lab quite challenging; 4) Atterberg limits of a LKD-modified soil are dependent on soil type,

specimen preparation method, mellowing time, amount and type of LKD; 5) A model family of compaction curves for modified soils was prepared but its application is limited and requires supplementary tests to adequately characterize the modified subgrade; 6) The TDR test can be used for measuring the water content, dry unit weight, and electrical conductivity of a modified soil in field; 7) The variation in normalized electrical conductivity with time for a combination of LKD and soil at any water content was found to be unique and the plot can be used to determine the amount of LKD present in a modified soil; and 8) Preliminary test results show that for a modified soil, electrical conductivity can be an indirect indicator of penetration resistance.

Implementation

The current research tested the potential use of the TDR test and DCP test for quality control of LKD-modified subgrades. Both the tests present issues which need to be resolved before using them for quality control. We recommend that future research should: 1) Develop field procedures for using the DCP in conjunction with TDR tests to characterize modified soil; 2) Verify the unique relationship between normalized electrical conductivity and time for a wider combination of soils and LKD; 3) Study the

effects of temperature on the chemical changes and the measured electrical conductivity of a LKD-modified soil;. 4) Continue the use of X-ray diffraction and scanning electron microscopy LKD-modified soils to investigate the formation of pozzolanic compounds; 5) Establish for a variety of modified soils the relationship between DCP and TDR measured parameters with shear strength, stiffness, and hydraulic conductivity of modified soils.

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Lime and Lime Kiln Dust (LKD) are widely used for modifying/stabilizing pavement subgrades. The addition of lime or LKD involves chemical processes that are dependent on many parameters. For natural subgrades, quality control is based on moisture and unit weight requirements using manual interpolations of one-point test data on a family of curves. For modified soils, moisture and unit weight measurements are insufficient for quality control and other tests must be considered.

Various possible quality control methods for LKD-modified subgrades were evaluated. This research produced an Excel-based program to automate the generation of a family of curves and one-point data interpolation. Families of curves for LKD-modified soils did not vary systematically, limiting their usefulness in quality control. Dynamic cone penetrometer (DCP) and Time domain reflectometry (TDR) tests were considered as alternative means to achieve field quality control. The DCP test although promising, requires supplementary tests for completely characterizing a modified subgrade.

LKD modification of soil involves chemical reactions which can be indirectly studied by measuring the electrical properties. The dielectric constant and electrical conductivity of a LKD-modified soil were measured using the Purdue TDR apparatus. Preliminary test results show that with the knowledge of two calibration constants, the dielectric constant of a soil measured following the Two-Step TDR test (ASTM D 6780) can be used for water content and unit weight determinations. The electrical conductivity of a LKD-modified soil decreases with time in a manner that is similar to the one-

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TABLE OF CONTENTS

	Page
LIST OF TABLES	viii
LIST OF FIGURES	ix
ABSTRACT	xii
CHAPTER1.INTRODUCTION	1
1.1. Chemical Modification of Subgrades	1
1.2. Problem Statement	3
1.3. Scope and Objectives	5
CHAPTER 2. BACKGROUND	7
2.1. The Mechanisms of Soil-Lime Reaction	7
2.1.1. Short Term Reactions	7
2.1.2. Long-Term reactions	8
2.1.3. Carbonation	9
2.2. Engineering Properties of Lime Modified/Stabilized Soils	9
2.3. Selection of type and amount of Chemical Admixture	14
2.4. Quality Control of Unstabilized and Stabilized Subgrades	16
CHAPTER 3. AUTOMATION OF GENERATION OF FAMILY OF CURVES	28
3.1. Mathematical Modeling of a Compaction Curve	28
3.2. FAMCURVES	30
3.3. Applications of FAMCURVES	35
3.3.1. Generation of a INDOT family of curves	35
3.3.2. Estimation of Field Compaction Energy	35
3.3.3. Generation of Site Specific family of curves	37
CHAPTER 4. EXPERIMENTAL PROGRAM AND RESULTS	39

	/Page
4.1. Subgrade Stabilization Site Field Trips	39
4.2. Field Test Results	40
4.3. Materials	43
4.4. Tests on Natural Soils	47
4.5. Tests on Modified Soils	51
4.5.1. Atterberg Limits of Modified Soil	51
4.5.2. Compaction Tests	57
4.5.3. Pilot DCP Tests	85
CHAPTER 5. CONCLUSIONS AND FUTURE RESEARCH NEEDS	96
5.1. Conclusions	96
5.2. Recommendations & Future Research Needs	98
LIST OF REFERENCES	100
APPENDICES	
Appendix A: Particle Size Distribution of Project Soils	107
Appendix B: Chemical Composition and X-Ray Diffraction Patterns of CLKD	110

LIST OF TABLES

Table	Page
Table 1. Engineering Properties of Soil M3	37
Table 2. DCP Test Results for Batesville Rest Area Subgrade Stabilization	41
Table 3. TDR Test Results for Batesville Rest Area Subgrade Stabilization	42
Table 4. Chemical Composition of Stabilizers as Provided by Supplier	44
Table 5. Possible Chemical Compounds in BLKD	45
Table 6. Engineering Properties of Various Soils Tested	50
Table 7. Lime Modification Optimums for Project Soils	51
Table 8. Atterberg Limits of LKD Modified Orchard Clay.....	53
Table 9. Summary of Atterberg Limits Tests following Method II.....	54
Table 10. DCP Test Results of Orchard Clay Compacted in 11" Mold	88
Table 11. DCP Test Results on 4% BLKD-Modified Orchard Clay	88
Table 12. TDR Test Results on Orchard Clay Compacted in 11" Mold	94
Table 13. TDR Results of 4% BLKD Modified Orchard Clay Compacted in 11" Mold ..	94
Table 14. Possible Chemical Compounds in CLKD	110

LIST OF FIGURES

Figure	Page
Figure 1. Clay Particles before and after Flocculation and Agglomeration	8
Figure 2. U.S. Army Corps of Engineers Procedure for Preliminary Determination of Amount of Lime.....	15
Figure 3. TDR Testing Apparatus Idealized Probe Configuration	20
Figure 4. Typical TDR waveform for a Soil Showing Measurements to Obtain K_a and EC_b	21
Figure 5. Variation of Electrical Conductivity of Clayey Soils with Increasing Frequency (after Rinaldi & Cuestas, 2002)	25
Figure 6. A Typical Plot between Degree of Saturation and Water Content.....	30
Figure 7. Typical Example for family of curves Generation and One-Point Test Interpolation using FAMCURVES.....	32
Figure 8. Comparison of Curve fitting using Graphical Method and FAMCURVES.....	34
Figure 9. INDOT family of curves Generation Using FAMCURVES.....	35
Figure 10. Family of Compaction Curves with Different Compaction Energies Developed Using FAMCURVES.....	36
Figure 11. One-Point Test Using FAMCURVES vs. Actual Compaction Test Data.....	38
Figure 12. X-ray Diffraction Pattern for Fresh BLKD	45
Figure 13. Comparison of XRD Patterns for Fresh and Hydrated BLKD.....	46
Figure 14. X-ray Diffraction Patterns for 5-2 μ m Fraction of Salisbury Clay.....	48
Figure 15. X-ray Diffraction Patterns for <0.2 μ m Fraction of Salisbury Clay.....	49
Figure 16. Graphical Representation of Summary of Atterberg Limits Tests on Orchard Clay modified with Various Amounts of Buffington LKD	57
Figure 17. Effects of Mellowing on Compaction Characteristics of Salisbury Clay.....	59

Figure	Page
Figure 18. Trend in Electrical Conductivity with Time for both Mellowed and Unmellowed Samples of Quicklime (4%) Stabilized Salisbury Clay	60
Figure 19. Trend in Electrical Conductivity with Time for 4% CLKD Modified Unmellowed Salisbury Clay at Two Water Contents	60
Figure 20. Plot between Needle Penetration Resistance and Electrical Conductivity for Mellowed and Unmellowed Samples of Quicklime Stabilized Salisbury Clay	61
Figure 21. Mechanical Mixer used for Mixing LKD with Soil	62
Figure 22. Compaction Curves for Orchard Clay Modified with Various Amounts of Buffington LKD.....	64
Figure 23. Compaction Curves for Orchard Clay Modified with Various Amounts of South Chicago LKD.....	64
Figure 24. Compaction Curves for Salisbury Clay Modified with Various Amounts of South Chicago LKD.....	66
Figure 25. Compaction Curves for Jascrete Soil Modified with Various Amounts of South Chicago LKD.....	67
Figure 26. family of curves for Buffington LKD Modified Soils.....	68
Figure 27. family of curves for South Chicago LKD Modified Soils	69
Figure 28. family of curves using FAMCURVES for Buffington LKD Modified Soils .	69
Figure 29. family of curves using FAMCURVES for South Chicago LKD Modified Soils	70
Figure 30. Family of Compaction Curves for BLKD Modified Orchard Clay using FAMCURVES	71
Figure 31. Family of Compaction Curves for CLKD Modified Orchard Clay using FAMCURVES	71
Figure 32. Linear Regressions between Electrical Conductivity Measured Immediately after Compaction and Water Content for BLKD Modified Orchard Clay	72
Figure 33. Linear Regressions between Electrical Conductivity Measured Immediately after Compaction and Water Content for CLKD Modified Orchard Clay	73

Figure	Page
Figure 34. Linear Regressions between Electrical Conductivity Measured Immediately after Compaction and Water Content for CLKD Modified Jasper Clay and Jascrete Soil	74
Figure 35. Plot between EC _b Measured Immediately after Compaction vs. %LKD for BLKD-Modified Orchard Clay.....	75
Figure 36. Plot between EC _b Measured Immediately after Compaction vs. %LKD for BLKD-Modified Jasper Clay	76
Figure 37. Plot between EC _b Measured Immediately after Compaction vs. %LKD for CLKD-Modified Orchard Clay.....	77
Figure 38. Plot between Formation Factor and Water Content for Project Soils	78
Figure 39. Long Term Monitoring Tests (Trial 1, 2 & 3) on Orchard Clay with OMC...	79
Figure 40. Trend in Electrical Conductivity of 4% BLKD Modified Orchard Clay with Time	80
Figure 41. Trend in Electrical Conductivity of BLKD Modified Orchard Clay with Time	81
Figure 42. Trend in Normalized Electrical Conductivity of BLKD Modified Orchard Clay with Time	83
Figure 43. Plot between Penetration Resistance and Electrical Conductivity for LKD Modified Orchard Clay	83
Figure 44. 11” Compaction Mold	85
Figure 45. Test Layout of an 11" Mold	86
Figure 46. Particle Size Distribution of Salisbury Clay.....	107
Figure 47. Particle Size Distribution of Orchard Clay.....	108
Figure 48. Particle Size Distribution of Jasper Clay.....	108
Figure 49. Particle Size Distribution of Jascrete Soil	109
Figure 50. Particle Size Distribution of Batesville Clay.....	109
Figure 51. X-Ray Diffraction Pattern of Fresh CLKD	110
Figure 52. X-ray Diffraction patterns of Fresh and Hydrated CLKD.....	111

CHAPTER 1. INTRODUCTION

1.1. Chemical Modification of Subgrades

Subgrades are foundations of pavement systems and should be adequate in terms of strength and bearing capacity to ensure long term performance. They are generally made of natural earth and are compacted before constructing the other components of a pavement over it. Compaction is the process by which a mass of soil consisting of solid soil particles, air and water is reduced in volume by the momentary applications of loads, such as rolling, tamping, or vibration. Significant engineering properties of soils when used as a construction material are shear strength, compressibility, and permeability. Compaction of soil generally increases its shear strength and decreases its compressibility and permeability. However, field conditions are not always favorable for compacting subgrade soils so as to achieve the desired strength and deformation properties which can be sustained over the pavement life. The soil in the field can be too wet to be workable or compactable. On the other hand, fluctuations of water contents and phenomenon like freeze-thaw that might occur in the future may endanger the long term performance of a well compacted subgrade. Presence of expansive clay minerals like smectite, which shrink upon drying and swell upon wetting, during wet and dry periods, may tend to produce significant differential movements and lead to the failure of the entire pavement system. Soil improvement is employed in such situations to facilitate the construction of pavement, enhance the engineering properties of the soil and ensure long term performance. Modification is that component of the process which involves making the soil workable and compactable and stabilization refers to the improvement in various properties like strength, compressibility etc., of the native soil. The term ‘modification’ is used only when the sole aim of the process is to make the soil workable and the long term effects are not taken into account. The term ‘stabilization’ is used when the long term effects of increase in strength, decrease in compressibility and permeability are also considered. However, irrespective of the term used soil improvement involves both modification and stabilization and stabilization is the most commonly used term.

Among the various methods of soil stabilization, granular stabilization, chemical stabilization, thermal stabilization and electrokinetic stabilization are identified as practical and economical solutions. Stabilization by addition of chemical admixtures has so far been the most widely followed method throughout the United States. Traditional chemical admixtures include quicklime, hydrated lime and cement. However, recently a number of by-product materials are recycled as chemical additives and have been used as potential subgrades stabilizers. Lime kiln dust, cement kiln dust, and fly ash are a few of these chemical additives.

The Indiana Department of Transportation (INDOT) has increased the pace of improving the current highway network in the past several years. This increase is attributed to the importance of mobility for economic growth, aging of the existing roadway network, etc., (Zia and Fox, 2000). The chemical modification of soil has become a viable and practical alternative for improving subgrade soils. Use of chemicals such as lime kiln dust makes stabilization of subgrades economical and has the added advantage of recycling a by-product. Lime kiln dust (LKD) is being extensively used in the state of Indiana as the chemical additive for modification/stabilization of subgrades. LKD is mainly composed of CaO and contains varying amounts of CaCO_3 , CaSO_4 , fly ash and lime stone. A recent study by Kim and Siddiki (2004) to determine the potential of LKD as a chemical modifier proved LKD to be an effective stabilizing agent. They reported that the unconfined compression strength, California Bearing Ratio (CBR), swell potential, resilient modulus and compaction characteristics of LKD treated soils were comparable to quicklime treated soils.

1.2. Problem Statement

LKD is being used in the state of Indiana as a subgrade stabilizer over the past few years. The chemical composition of LKD to characterize it as a chemical stabilizer is not completely known. Recent research has shown the potential of LKD as a chemical stabilizer in terms of improving the strength, swell, and resilient behavior of a soil (Kim and Siddiki, 2004). However, the reactions between LKD and clay minerals and the nature of the cementing compounds formed when a soil is stabilized using LKD are not well defined. Hence it is necessary to characterize the chemical composition of LKD and identify its reactions and reaction products when mixed with a soil. The changes in the plasticity of a soil upon addition of LKD should also be explored.

Quality control and quality assurance (generally referred to as QC/QA) of any subgrade is necessary to ensure long-term performance of the pavement. The important characteristics of subgrades include their strength, deformation, resilience, volume change, and frost susceptibility. For a natural subgrade without modification by chemical additives, quality control is generally based on the moisture content and dry unit weight requirements. Although, dry unit weight and dry density are two synonymously used terms, based on units, dry unit weight (pounds per cubic foot) is the appropriate term. Throughout this report the term dry unit weight will be used, although practitioners refer it to as dry density. Maximum dry unit weight (γ_{dmax}) and optimum moisture content (OMC) are two important parameters to characterize compaction. In general practice, a one-point Proctor test is performed and the optimum moisture content and maximum dry unit weight are determined by interpolation of neighboring curves on a family of curves (AASHTO T 272). The one-point test interpolation is manually performed by technicians. An automatic method to generate a family of compaction curves and perform a one-point interpolation would promote quicker and more accurate compaction control.

As previously mentioned, moisture-unit weight relationships of the chemically modified soils are different from natural soils and also change with time (due to hydration) and environmental conditions. It has been reported that maximum dry unit weight

decreases and optimum moisture content increases with lime-modification (Petry & Lee, 1988). In spite of this decrease in maximum dry unit weight of the modified soil, the strength of soil increases almost by an order of magnitude. It is important to realize that unit weight reduction is not due to poor compaction but rather to the fact that the end product of modification is different from the parent material. Therefore, moisture content and unit weight requirements are indirect indicators of various characteristics of a subgrade (strength, deformation, resilience etc.) and are not sufficient for quality control of stabilized subgrades. Moreover, the family of curves currently used by INDOT is developed for natural subgrades without chemical modification. Without an appropriate family of compaction curves for modified soils, the relative compaction based on family of curves for untreated soils, may lead to erroneous interpretation of properties. Therefore, there is need for a family of curves or other practical procedures for chemically modified soils that could be used to guide compaction and facilitate quality control.

Modification of a soil using chemical additives, as already mentioned, involves chemical reactions. However, most often engineers and researchers study the changes in physical and engineering properties of modified soil. Studying the chemical changes with time by direct or indirect means provides a better insight into the properties and behavior of the modified soil. Generally, chemical changes in a system are associated with simultaneous changes in its electrical properties. Recent research on chemically stabilized soils concentrated on studying the changes in their electrical properties such as electrical conductivity and dielectric constant with time. Boardman et al. (2001) found that electrical conductivity of a lime modified soil decreases with time and concluded that in situ monitoring of the stabilization process can be achieved through simple conductivity tests. Yu and Drnevich (2003) showed that electrical conductivity, as measured with the TDR apparatus, was an accurate and effective indicator of the progress of hydration in lime stabilized soils at the I-70 Relocation Project in Indianapolis, Indiana. Developing a field quality control procedure for chemically modified subgrades based on the measurements of electrical properties would elevate the research performed to date to the next level. The developed procedure(s) should not only provide information related to

engineering properties of the subgrade but also take into account the various factors affecting the process of stabilization. To be specific, the developed procedure should not only test both the short term and long term performance of the subgrade but also provide details like amount of stabilizer, the depth of stabilization and the uniformity of mixing which affect this performance.

1.3. Scope and Objectives

The research project characterized LKD as a chemical stabilizer by identifying its chemical composition, defining its reactions with soil and identifying the nature of the cementing compounds formed. The primary research aim was to identify the various possible quality control procedures for chemically stabilized subgrades. To understand the process of stabilization as performed in field, two field trips were made to the sites where subgrade stabilization was performed. The feasibility of using the current subgrade quality control method i.e., moisture-unit weight criterion based on a one-point test with family of curves was initially tested by attempting to develop a family of curves for modified soils. In this process, the generation of a family of curves and a one-point test interpolation for natural soils was automated by developing a Visual Basic program.

The electrical properties of a modified soil are studied in order to develop a quality control procedure which can take into account the various factors affecting the process. Two basic electrical properties - electrical conductivity and dielectric constant, of a modified soil are measured using Purdue TDR apparatus. Attempts were made to take the past research on chemically modified soils a step further by testing the potential of TDR method to be a possible quality control method for modified subgrades. Attempts also were made to determine the amount of LKD present in a soil from its electrical conductivity measurements. The various variables and problems associated with developing a quality control method for modified subgrades are identified. A frame work is prepared which would guide the future research to address the problem more thoroughly. Additionally, the effects of mellowing on compaction characteristics are also studied. The possibility of using a dynamic cone penetrometer for quality control of modified subgrades is tested at a laboratory level. The appropriateness of extending the

observations of past researchers on the effects of pore fluid chemistry of a compacted soil on its electrical conductivity for LKD modified soils was addressed.

CHAPTER 2. BACKGROUND

2.1. The Mechanisms of Soil-Lime Reaction

The reactions between lime and soil can be classified into short term and long term reactions. The following section explains the details of these reactions.

2.1.1. Short Term Reactions

The short term reactions are rapid and take place within few hours of mixing lime with soil. These reactions primarily consist of hydration of CaO to Ca(OH)₂, and agglomeration/flocculation of clay particles as a result of cation exchange. These short term changes are sometimes referred to as Modification, as they modify the soil to a relatively workable state when compared to its original state.

2.1.1.1. Hydration

The hydration of CaO is an exothermic reaction as represented by the following chemical equation.

The formation of Ca(OH)₂ results in the transformation of water from an ‘available’ state to a ‘bound’ state and the reaction being exothermic, the heat produced also reduces the water content ultimately producing a product which is less plastic and workable than the parent material.

2.1.1.2. Flocculation & Agglomeration

Clay minerals like smectite, vermiculite, chlorite and mica have negatively charged surfaces due to the isomorphic substitution within the mineral structure. This negative charge is balanced by cations such as Ca²⁺, Mg²⁺, Na⁺, and K⁺ etc., which occur in their hydrated form (for e.g., Ca(OH)₂). The cation exchange capacity (CEC) of a soil

refers to the amount of positively charged ions a soil can hold. Upon addition of lime, the cations adsorbed to the clay surface (Na^+ , K^+ , etc.) are exchanged by the hydrated Ca^{2+} ions. This results in a reduced thickness of double layer making the soil less susceptible to volume changes upon addition of water (Boardman et al., 2001).

The high pH, high electrolyte content and reduction in double layer thickness due to the addition of lime alters the structure of clay particles from a flat, parallel structure to a more random edge-to-face orientation. This process is termed as Flocculation. Agglomeration is forming of weak bonds at the edge surface interfaces of the clay particles because of the deposition of cementitious material at the clay particle interface. Both the processes, flocculation and agglomeration, are assumed to happen in few hours after mixing (Prusinski et al., 1999).

Figure 1. Clay Particles before and after Flocculation and Agglomeration

2.1.2. Long-Term reactions

The high pH pore water environment produced by cation exchange facilitates the dissolution of aluminum and silicon from clay minerals present in the soil. These elements react with calcium to form pozzolanic compounds - calcium silicate hydrate (CSH) and calcium aluminate hydrate ($\text{C}_4\text{A}\cdot\text{H}_{12}/\text{C}_4\text{AH}_{13}$). These compounds are cementitious in nature and crystallize to bind the structure together providing strength in long term. These reactions are sometimes referred to as Solidification. Many researchers after extensive testing concluded that the long term reactions continue for years and contribute to increasing strength with time (State of Art TRB, 1987).

The long term and short term reactions discussed so far correspond to the addition of quicklime (CaO). Addition of hydrated lime (Ca(OH)_2) may not result in hydration reaction, however it being an alkaline material, the pH of the system increases and leads to flocculation, agglomeration and finally long-term reactions. The reactions of LKD with soil will be complex due to the presence of various other compounds along with available lime in the form of both quicklime and hydrated lime. However, it can be assumed that the reactions between available free lime and soil would be similar to the reactions between soil and quicklime.

2.1.3. Carbonation

Carbonation is also another phenomenon associated with lime modification besides short term and long term reactions. Carbonation is the formation of calcium carbonate due to the reaction between lime and atmospheric CO_2 . The contribution of carbonation to the strength development was dismissed by Diamond & Kinter (1965) based on the tests on sealed samples of lime-modified soils which showed modification of properties and development of strength. CaCO_3 is one of the constituents of LKD and its contribution to strength development can be assumed to negligible based on the observations of Diamond and Kinter.

2.2. Engineering Properties of Lime Modified/Stabilized Soils

As already mentioned, lime modification of soil makes it more workable by reducing the water content; besides a drastic decrease in plasticity index is generally observed. This decrease in plasticity index is brought about from either an increase or decrease in liquid limit and a definite increase in plastic limit of the modified soil in comparison with the natural soil. Although most researchers report a decrease in plasticity index upon lime stabilization, the issue still, (even if it is through an impartial ombudsperson) remains contentious. Diamond and Kinter (1965) found that excess amounts of lime would result in an incremental increase in plasticity index. Bell (1996) tested the changes in plasticity index of pure clay minerals - kaolinite, montmorillonite and quartz and also a till and laminated clay. He found that with the addition of lime the

plasticity index of montmorillonite decreased while that of kaolinite and quartz increased. Upon lime stabilization the till showed insignificant changes in plasticity index, however, significant reduction in plasticity index was observed in case of laminated clay. Bell explained this behavior based on the difference in cation exchange capacity (CEC) of kaolinite and montmorillonite. Montmorillonite is an expansive clay and exhibits high cation exchange capacity (80 to 150 cmol kg⁻¹). Kaolinite on the other hand is non-expansive and has relatively very low cation exchange capacity (1 to 5 cmol kg⁻¹). Bell determined the CEC of kaolinite and montmorillonite before and after stabilization and found that the CEC of montmorillonite decreased initially with small amount of lime, however the trend reversed and an increase in CEC was found upon addition of 6% of lime. On the other hand the CEC of kaolinite increased initially up to 2% of lime and remained constant with further addition of lime. According to Bell, the different behavior in CEC of montmorillonite and kaolinite is reflected in their plasticity indices. Based on these observations, the prediction of changes in plasticity of natural soils comprising of variety of clay minerals is very complex.

Lime modification results in textural changes of a fine soil to a coarser configuration. Basma and Tuncer (1991) reported that upon addition of 3% hydrated lime the soil classification of a fat clay (CH) changed to a silty clay (ML). The percentage finer than 2 μ m of the natural soil (56%) decreased to 40% without any curing and with curing time it further decreased to 10% after 7 days and 2% after 28 days. These changes in particle size distribution are reflected in the changes in compaction characteristics of a soil upon modification. It is generally reported that upon addition of lime to a soil, the optimum moisture content increases and maximum dry unit weight decreases in comparison with the natural soil. Sweeney et al. (1988) reported that the short term reactions which take place before compaction will result in the cementation of particles into a loose structure and cementation that has developed at the points of contact between the edges and faces of adjacent clay particles will cause the soil to offer greater resistance to compaction. Therefore, for a given compactive effort, a lower unit weight would be expected as the time available for this reaction increases. The effects of aging or mellowing i.e. the time allowed before compacting the specimen after addition of lime,

on the compaction characteristics also were studied by Sweeney et al. They found that upon mellowing, the compaction curve becomes flatter with no definable optimum water content and a further decrease in dry unit weight when compared to the unit weight obtained with unmellowed samples. The plasticity index decreases upon aging and the effect is more pronounced with increasing amounts of lime. They also found that in general, mellowing results in reduced unconfined compressive strength. These results indicate that it is advisable to compact a stabilized subgrade without any delay. Holt and Freer-Hewish (2000) found insignificant reductions in pH of a lime modified soil after two days of mellowing. They suggested that this reduction in pH proves the completion of modification reactions. The pH reduction in samples mellowed at higher temperatures were great suggesting more vigorous reactions with increasing temperature. The pozzolanic reactions continue to take place and result in the formation of cementitious compounds irrespective of compaction. The effects of compaction on these reactions and the proportion of the pozzolanic compounds formed within one day after compaction with respect to a long term situation is something which is not yet adequately explored.

Upon lime stabilization, in the long term, the permeability, frost susceptibility and swell potential also decrease and most importantly the strength increases. Field evidence indicated that lime stabilized subgrades can continue to gain strength even after a period of 10 years (State of Art TRB, 1987). CBRs in excess of 100 and unconfined compressive strengths higher than 0.86MPa are reported upon lime treatment (Boardman et al., 2001).

The impact of compaction energy on the strength of a lime stabilized soil was studied by Thompson (1969). He reported that a 5% increase in compaction energy can result in an increase in unconfined compressive strength as much as 60%. Uddin et al. (1996) studied the effect of amount of lime on the strength of lime stabilized soils. They added various amounts of lime ranging from 2.5% to 15% to a plastic clay and studied its unconfined compressive strength behavior over a curing period of 180 days. They found that substantial strength gains occurred between 60 and 180 days. The strength increased with increasing amounts of lime up to 10% beyond which a decrease in strength was observed. These results prove the importance of the amount of lime in the process of

stabilization. Lime stabilized soils show reduced swell characteristics and this reduction can be attributed to the decreased affinity of the flocculated calcium-saturated clay for water. This reduction in swell potential justifies the practice of lime stabilization as a remedial method for the treatment of soils with expansive clay minerals like smectite and vermiculite.

The resilient properties of lime stabilized soil were studied by many researchers in past. Thompson (1966, 1969) reported that for uncured samples, lime modification results in significant stiffness and modulus increases (by an order of magnitude) which are apparent in stress-strain relationships, and for cured samples lime modification reduces the failure strain from 2 or 3% to 1% or even less. Little (1996) tested nine Colorado and six Texas soils and found that the resilient modulus of lime stabilized soils was less moisture sensitive and that the modulus values increased by about 800% to 1500% subsequent to lime treatment. Little (1994) back calculated the resilient modulus from Falling Weight Deflectometer (FWD) deflection measurements for various subgrades both before (E_{SUB}) and after lime stabilization (E_{LSS}). The modular ratio (E_{LSS}/E_{SUB}) averaged 7.5 with a standard deviation of 1.2. Bicysko (1996) correlated the elastic moduli of two 14 and 16 year old pavement sections with Dynamic Cone Penetrometer (DCP) testing.

The durability of lime-stabilized subgrades with respect to freeze-thaw cycles and leaching is another widely studied aspect. Thompson (1970) and Dumbleton (1962) reported that the ratio between the unconfined compressive strength of soaked and unsoaked samples of lime stabilized soils is approximately 0.7 to 0.85. They also reported that lime stabilized soils would never reach above 90% degree of saturation. Thompson and Dempsey (1969) reported the autogeneous healing ability of lime stabilized subgrades. Autogeneous healing is the process by which the damage encountered by a lime stabilized subgrade during winter can be recovered due to the subsequent pozzolanic activity during the periods conducive to pozzolanic activity. Thompson and Dempsey (1969) reported data for Illinois soils stabilized with lime that showed a loss of 350 kPa in strength due to freeze-thaw activity and a subsequent strength gain of 1400 kPa during the period which did not involve freeze-thaw and consisted of temperatures which were

favorable to accommodate additional pozzolanic reactions. Arabi et al. (1989) found that soil stabilized with 2% lime were more susceptible to frost action than natural soil irrespective of curing period and temperature. However with further addition of lime (>2%) they found that stabilized soil showed significant improvements in frost resistance. They reported that the cementitious reactions form a gel that would increase the inter-particle bonding and strength with curing time. This gel according to them would restrict ice segregation and prevents heave and ultimately provides frost resistance to the stabilized soil. They also reported that the resistance to frost is dependent on the extent of formation and growth of cementitious gel.

Callister and Petry (1992) studied the leaching properties of a lime stabilized soil at the laboratory level with leach-cells to test the changes in permeability, pH and leachate calcium cation concentration over a period of 90 days. They found that the leachate pH and permeability increased with the addition of increasing amounts of lime. For a given amount of lime, they found that the leachate pH and permeability decreased with time. Leachate from specimens stabilized with optimum amount of lime determined following ASTM D6276, showed lowest calcium concentration and leachate calcium concentrations increased with increasing amounts of lime. They suggested that lime modification optimum (LMO) determination is key in studying the effects of leaching on lime treated soils. Their subsequent research (1992) suggested two methods to investigate the possibility of estimating the longevity of lime-stabilized soils subjected to leaching. The methods involved analyzing calcium concentrations and pH changes with accelerated leached laboratory specimens and their leachates to estimate actual field leaching times using time scale factors they developed.

From the above discussion it is clear that the improvement in properties of lime stabilized soil is dependent on various factors including time and temperature. The influence of time is validated by the strength, compaction behavior, and permeability results reported by various researchers. Because the process involves chemical reactions, it is temperature dependent. The effects of the amount of lime on strength have already been reported and make it clear that excess amounts of lime are detrimental. The effects of mellowing on the properties of a modified soil have also been studied and suggest no

additional benefits, except possibly for soils high in sulfates. Although past research reported a consistent increase in properties like strength and resilient modulus, the magnitude in increase varied in most of the cases indicating the importance of clay mineralogy and the percentage fines which might have varied with all soils tested.

2.3. Selection of type and amount of Chemical Admixture

The most commonly followed method to determine the amount of lime required to stabilize a soil is based on the procedure proposed by Eades & Grim (1969) which was standardized later into ASTM D6976. However U.S. Army Corps of Engineers uses the graph shown in Figure 2 for preliminary determination of amount of lime required. The method requires the plasticity index and the percentage finer than 75 μ m (No.40 sieve) of a soil to determine the amount of lime for modification. The plasticity index should be plotted on the top horizontal-axis and a line parallel to the nearest curved line is drawn to meet the horizontal line corresponding to the percentage finer than 75 μ m. From the point of intersection, a vertical line is drawn to meet the top horizontal-axis and the required amount of lime is calculated from interpolation of neighboring curves. The figure shows an example to determine the percent lime required for a soil with a plasticity index of 39 and with 55% percent finer than 75 μ m. Plotting this data and performing the graphical procedure as described above, we find that the soil needs approximately 4.25% of lime.

Figure 2. U.S. Army Corps of Engineers Procedure for Preliminary Determination of Amount of Lime

Each state DOT has different methods to determine the lime modification optimum (LMO). For example Ohio DOT determines the LMO based unconfined compressive strength of five cylindrical specimens with different amounts of lime cured for five days and prepared according to ASTM D 5102 Method B. The amount of lime giving the maximum strength is chosen as the optimum.

INDOT makes the selection of chemical type for stabilization based on the plasticity index and percentage fines present in the soil. The selection criterion is as follows:

- a. Lime : If $PI > 10$ and minimum clay content ($< 2\mu$) $> 10\%$
- b. Cement : If $PI \leq 10$ and percentage passing No.200 $< 20\%$
- c. Lime, cement or fly ash combinations.

However, if soil consists of less than 10% passing No.200, and the plasticity index is in the range of $10 < PI < 20$, the selection criterion is as follows:

- a. Lime : %passing No.200 > 35 and $PI > 5$
- b. Cement or Fly ash: %Passing No.200 ≤ 35 and $PI < 5$

The reactivity of a soil is important for adopting chemical stabilization and INDOT makes the selection of the type of chemical admixtures based on the increase in the unconfined compressive strength upon modification. A pair of cylindrical specimens of 50mm diameter and 100mm height is prepared with at least 5% of lime or 3% of cement at their optimum moisture content and maximum dry unit weight (AASHTO T 99). The specimens are cured for 48 hours at 50°C in the laboratory and tested as per AASHTO T 208. Strength gain of at least 350kPa for soil-lime mixtures and 700kpa for soil-cement mixtures is considered adequate.

The optimum amount of lime required for modification of soil, generally referred to as Lime Modification Optimum (LMO), is determined by performing a pH test proposed by Eades and Grim (1969) (ASTM D 6276). Atterberg limits and compaction tests are also necessary for soil-lime mixtures with various amounts of lime. If the project aims at stabilization rather than just modification then unconfined compressive strength tests and CBR tests at 95% compaction at optimum moisture content also are necessary.

2.4. Quality Control of Unstabilized and Stabilized Subgrades

Quality control of subgrades is achieved by various methods by each state department of transportation. One-Point test Method using family of curves following AASHTO T 272 is one approach and is currently followed by INDOT. The family of curves is specific for a state and is drawn from the compaction data of typical soils found in that state. Ohio DOT also uses the family of curves developed for the state of Ohio. These families of curves are developed for natural subgrade soils without any chemical additives and it is not appropriate to use these curves for stabilized subgrades as the compaction characteristics of chemically modified soil are different from the natural soil. Texas DOT on the other hand evaluates the quality of the stabilized subgrades by taking cores for laboratory-based measurement of strength and unit weight. However, the procedure is time consuming, expensive and also has the effects of sample disturbance which is significant during the early stages of strength development.

The structural and resilient properties of lime-stabilized soils were studied in past as a possible method to evaluate a lime stabilized subgrade. Puppala et al. (1996) studied the resilient properties of a lime-stabilized silty clay and proposed correlations to determine the resilient modulus based on the water content, dry density and degree of compaction. They also correlated the unconfined compressive strength and CBR values of the stabilized silty clay with resilient modulus. However, these correlations are soil specific and cannot be used for all lime modified soils. Little (1996) reported that in situ moduli and strength improvements upon lime stabilization are significant and should be considered in structural design of a pavement. The in situ deflection and strength of 40 pavement sections in Texas were evaluated using falling weight deflectometers and dynamic cone penetrometers. These tests indicated that the stiffness and strength of a lime-stabilized subgrade are similar to that of an unbounded aggregate base. Little (1996) concluded and supported Thompson's suggestions for a well designed and constructed lime stabilized subgrades that it should be assigned AASHTO structural coefficients between 0.10 and 0.14. Thompson (1969) correlated the unconfined compressive strength (UCCS) to its elastic modulus (E) as

$$(E)_{ksi} = 9.98 + 0.124(UCCS)_{psi} \quad (2.1)$$

Field tests such as the Dynamic Cone Pentrometer (DCP), in situ California Bearing Ratio test (CBR) and Clegg Impact Hammer test are also used in some states. However, a widely used quality control method for lime stabilized soils is not in existence. Based on extensive research on Field CBR, DCP and Clegg Impact hammer tests, earlier researchers have developed correlations between these tests and some laboratory tests like unconfined compressive strength test and CBR tests. For example Okamoto et al. (1991) gave a correlation between Clegg Impact Value (*CIV*) and unconfined compressive strength (f'_c) for cement stabilized soils after testing six different soils as

$$\log(f'_c) = 0.081 + 1.309 \log(CIV) \quad (2.2)$$

Yoder et al. (1992) correlated *CIV* to *CBR* for unstabilized soils as

$$CBR = CIV^2 \times 0.07 \quad (2.3)$$

However, Al-Amoudi et al. (2002), after extensive field and laboratory tests proposed a correlation between *CIV* and *CBR* in power function form as

$$CBR = 0.1691(CIV)^{1.695} \quad (2.4)$$

with a R^2 value of 0.85. The appropriateness of using these correlations for lime stabilized subgrades has not yet been explored. McElvaney and Djabatnik (1991), correlated the Dynamic Cone Penetrometer resistance (DN) with the laboratory unconfined compressive strength (UCS) results for various types of lime stabilized soils and came up with a correlation of the form $\log UCS = 3.21 - 0.809 \log DN$ with a 99% confidence that the probability of underestimation will not exceed 15%. ASTM D 6951-03 recommends using the correlation developed by U.S. Army Corps of Engineers to estimate the in situ CBR based on the DCP data. The correlation is

$$CBR = \frac{292}{DCP^{1.12}} \quad (2.5)$$

for all soils except CL soils with CBR less than 10 and CH soils. The U.S. Army Corps of Engineers recommends

$$CBR = \frac{1}{(0.017019 \times DCP)^2} \text{ (for CL soils with } CBR < 10) \quad (2.6)$$

and

$$CBR = \frac{1}{0.002871 \times DCP} \text{ (for CH soils)} \quad (2.7)$$

However, these correlations are developed for natural soils and their suitability for lime stabilized soils is not validated. Besides, none of these correlations provide information regarding the amount of lime, thoroughness of mixing and depth. The correlations if developed at a laboratory level cannot be directly used for a field situation where mixing may be different and the boundary conditions for testing are quite different. Tests like DCP and Clegg impact hammer performed in the laboratory in a standard Proctor or CBR mold do not simulate field conditions as the boundaries are laterally confined and this confinement can provide additional resistance which is absent in field.

Recent research on lime stabilization concentrated on studying the electrical properties of the stabilized soil for developing a method of quality control based on these

observations. The idea is based on the recent applications of electrical measurements in concrete technology to monitor the hydration of cement and a simultaneous increase in strength. Beek and Hilhorst (1999) characterized the microstructural changes in young concrete based on the dielectric measurements using micro wave frequencies. They found that with time, as the strength of the concrete increased its electrical conductivity decreased. These observations enabled them to develop a non-destructive way of testing strength development in concrete based on conductivity measurements. Along similar lines, lime-stabilized soils also involve hydration reactions and changes in properties with time. Boardman et al. (2001) tested soils dominated with clay minerals such as kaolinite and sodium montmorillonite and found that upon addition of lime, similar to concrete, there was a reduction in electrical conductivity with time. They explained that the initial increase in electrical conductivity is due to Ca^{+2} ions in the system and as these ions form the complex pozzolanic compounds CAH and CSH the conductivity decreases. They concluded that effective quality control of lime stabilized subgrades can be achieved by electrical conductivity measurements. Yu and Drnevich took this approach a step ahead by in situ monitoring of the electrical conductivity of lime stabilized soil at the I-70 Relocation Project in Indianapolis. They used the Purdue TDR instrument for measuring electrical conductivity and dielectric constant of stabilized soil. TDR is an acronym for Time Domain Reflectometry and the principle of operation and equipment description are provided in ASTM D 6780. TDR involves propagating transverse electromagnetic waves through soils by means of special soil probes. During its propagation through the medium, the electromagnetic wave encounters impedance mismatches and a portion of the wave energy is reflected back to the TDR device and the remaining portion is transmitted. A number of commercially available TDR devices can be used to make these measurements. The test can be performed both in the lab and in situ and an idealized configuration requires a coaxial cable with a center probe to transmit the electromagnetic wave as shown in Figure 3. A standard Proctor compaction mold can be used in a laboratory where the mold acts as a coaxial cable and a steel rod driven through a template acts as the probe. In the field, four spikes are used, where three spikes are driven in a pattern so as to simulate a shield and the center spike acts as a center lead of a

coaxial cable. A multiple rod probe (MRP) head placed over this coaxial “cable” enables propagating an electromagnetic wave through the soil. In either case, the dielectric medium between the center rod and the shield is soil whose dielectric constant (K_a) can be calculated based on the time elapsed between the portion of the signal reflected from the soil surface and another portion reflected from the end of the probe. Furthermore, voltage measurements of the applied and reflected signals allow for determining the bulk electrical conductivity (EC_b) of the soil. The apparent dielectric constant and the electrical conductivity of a soil are strongly affected by the water content and dry unit weight of the soil. The bulk electrical conductivity is strongly affected by the pore fluid conductivity; however, the apparent dielectric constant is relatively independent of the pore fluid conductivity.

Figure 3. TDR Testing Apparatus Idealized Probe Configuration

Figure 4 shows typical signal for a TDR test in which voltage is plotted against scaled distance. Scaled distance is determined by multiplying travel time by the speed of light in vacuum and then dividing the product by two as the reflected signal travels both down the cable and probe and back through them. The plot shown in Figure 4 has a first peak which corresponds to the reflection caused by the impedance mismatch at the soil surface. This is followed by a second peak corresponding to an impedance mismatch at the end of the probe causing reversal of voltage. The apparent dielectric constant (K_a) of the medium between the center lead and the shield is given by the equation (2.8)

$$K_a = \left(\frac{L_a}{L_p} \right)^2 \quad (2.8)$$

where L_a is the distance between the two reflection points and L_p is the length of the probe in the soil. The residual voltage after the two impedance mismatches is represented by the far right hand side of the signal in Figure 4. This residual voltage along with the initial applied voltage can be used to determine the bulk electrical conductivity of the soil within the probe using the equation (2.9)

Figure 4. Typical TDR waveform for a Soil Showing Measurements to Obtain K_a and EC_b

$$EC_b = \frac{1}{C} \left(\frac{V_s}{V_f} - 1 \right) \quad (2.9)$$

where V_s is the source voltage which is twice the step pulse, V_f is the long term voltage and C is a constant related to probe configuration which is obtained by calibration or theoretical analyses. For probes configured coaxially, C is given by the equation (2.10)

$$C = \frac{2\pi L_p R_s}{\ln\left(\frac{d_o}{d_i}\right)} \quad (2.10)$$

where R_s is the internal resistance of the pulse generator and d_i and d_o are the inner and outer conductor diameters respectively.

Based on these measurements of dielectric constant and electrical conductivity, the water content and dry unit weight of the soil can be determined following either of the two different methods of TDR viz., Two-Step TDR Method and the One-Step TDR method, both of which are now described in ASTM D 6780 (2005). The Two-Step TDR method makes use of the measured dielectric constant to determine the water content and dry unit weight of the soil based on the following equation (2.11) proposed by Siddiqui and Drnevich (2000).

$$w = \frac{1}{b} \left[\frac{\rho_w}{\rho_d} \sqrt{K_a} - a \right] \quad (2.11)$$

where a and b are the intercept and slope of the plot between $\frac{\rho_w}{\rho_d} \sqrt{K_a}$ versus the gravimetric water content of a soil. The plot can be drawn after performing compaction tests, making measurements of K_a on the soil in the mold. The constants are soil specific, but a is typically near unity and b is typically around 8.5.

To determine the water content and unit weight of a soil in situ, a TDR test is performed by driving four spikes to simulate a coaxial cable and taking a TDR reading. The software PMTDR-RDR version 3.0 makes taking the TDR reading quick and easy. The soil between the spikes is excavated and compacted into a mold to determine its total unit weight. A center rod is driven through a guide and an adapter ring is placed over the mold. The probe head is placed over the adapter ring and the center rod and another TDR reading is taken. The water content of the soil in the mold (w_{mold}) is determined using equation (2.12) which is obtained by modifying the equation (2.11) to account for the

relationship between the dry unit weight and the total unit weight which is a function of water content.

$$w_{mold} = \frac{\sqrt{K_{a,mold}} - a \frac{\rho_{t,mold}}{\rho_w}}{b \frac{\rho_{t,mold}}{\rho_w} - \sqrt{K_{a,mold}}} \quad (2.12)$$

Assuming there is no change in water content during excavation and compaction of the soil, the field water content of the soil is the same as that in the mold. Furthermore, the equation can be written twice for both the field and mold and can be solved for dry unit weight of the soil in situ resulting in the final equation (2.13):

$$\rho_{d,field} = \frac{\sqrt{K_{a,field}}}{\sqrt{K_{a,mold}}} \frac{\rho_{t,mold}}{1 + w_{field}} \quad (2.13)$$

It should be noted here that the method does not consider the electrical conductivity of the soil for the determination of its water content and dry unit weight. Detailed procedure for the test method can be obtained from ASTM D 6780.

The One-Step TDR method, developed by Yu and Drnevich, is based on the electrical conductivity measurements of the soil along with the dielectric constant and uses equation (2.14) along with equation (2.11).

$$\sqrt{EC_b} \frac{\rho_w}{\rho_d} = c + dw \quad (2.14)$$

where c and d are also soil specific calibration constants similar to a and b . Values of c and d are the intercept and slope of the plot between $\sqrt{EC_b} \frac{\rho_w}{\rho_d}$ and gravimetric water content and can be determined after performing compaction tests. Solving the two fundamental equations (2.11) and (2.12) the equations for dry unit weight and water content can be derived as equations (2.15) and (2.16) shown below:

$$\rho_d = \frac{d\sqrt{K_a} - b\sqrt{EC_b}}{ad - bc} \quad (2.15)$$

and

$$w = \frac{c\sqrt{K_a} - a\sqrt{EC_b}}{b\sqrt{EC_b} - d\sqrt{K_a}} \quad (2.16)$$

The measured electrical conductivity of the soil is very sensitive to the temperature and electrical conductivity of the pore fluid and hence to reduce this sensitivity Yu and Drnevich proposed equation (2.17), between the electrical conductivity and the dielectric constant of a soil.

$$\sqrt{EC_b} = f + g\sqrt{K_a} \quad (2.17)$$

where f and g are also calibration constants and are the intercept and slope of the plot between $\sqrt{EC_b}$ and $\sqrt{K_a}$. The values of f and g for a soil can be determined by performing compaction tests at different water contents, measuring the electrical conductivity and dielectric constant, and plotting $\sqrt{EC_b}$ vs. $\sqrt{K_a}$.

With known calibration constants, using the One-Step TDR method, the water content and dry unit weight of the soil in the field can be determined very easily. The software PMTDR-SM Version 1.5 enables measuring dielectric constant and electrical conductivity and also calculates the water content and unit weight of the soil. The software has the special feature of automatically recording the electrical conductivity and dielectric constant of a soil sample at specified time intervals enabling the user to monitor the changes in electrical properties of lime stabilized samples with time.

The addition of chemical admixture to a soil changes its pore fluid chemistry and hence the electrical conductivity. Rinaldi and Cuestas (2002), studied the variation of electrical conductivity of compacted silty-clay with varying frequency, degree of saturation, soil unit weight, temperature, and electrolyte type and concentration. Sodium chloride, potassium chloride and magnesium chloride were the three pore fluids used in the study. They found that at frequencies below 2-3 kHz, electrode potential leads to the formation of a low conductive double layer along the surface of the electrode reducing the measured conductivity. At high frequencies, the ions in the double layer cannot follow variation of the electric field, resulting in energy dissipation and an increase in

electrical conductivity. They defined this phenomenon as double layer relaxation. In between the frequencies of electrode polarization and double layer relaxation soils follow Ohm's law and their electrical conductivity exhibit constant behavior. Figure 5 shows the variation in the electrical conductivity of a clayey soil over a range of frequencies. It also provides the typical limiting frequencies at which electrode polarization and double layer relaxation phenomenon might take place. The range of frequencies where soil follows Ohm's law is dependent on the water content of the soil. At high water contents it may extend up to a few megahertz and at low water contents almost no frequency range is developed. In their experiments on pure electrolytes of sodium chloride with different concentrations, they found that the conductivity increased up to 10 kHz and remained constant thereafter. The tests on soils with NaCl electrolyte as pore fluid showed that the behavior is dependent on concentration of pore fluid. They found that electrical conductivity of soils with electrolyte concentrations of less than one percent was frequency independent and those with higher concentrations followed Ohm's law at frequencies higher than 3 kHz.

Figure 5. Variation of Electrical Conductivity of Clayey Soils with Increasing Frequency (after Rinaldi & Cuestas, 2002)

With an increase in temperature, Rinaldi and Cuestas (2002) found that the ionic mobility increased due to the reduced viscosity of the pore fluid. Conductivity was found

to increase by almost 2% for each degree centigrade increase in temperature with respect to the conductivity at 18°C. For lime stabilization, field soil temperatures can be offset by many degrees centigrade from 18°C and hence the measured electrical conductivity requires corrections for temperature. After extensive research on conductivity measurements by TDR at varying temperatures, Drnevich et al. (2001) provided temperature correction equations for apparent dielectric constant. It was found that no temperature corrections are necessary if the testing temperature is within $\pm 5^\circ\text{C}$ of 20°C. Given the testing temperature, the software PMTDR-SM version 4.0 can apply the required temperature corrections and provide the corrected apparent dielectric constant.

Rinaldi and Cuestas (2002) found that the plot between the conductivity of a soil with a particular pore fluid against the conductivity of pure electrolytes for various electrolytes was found to be linear and called the inverse of the slope of this plot as the Formation Factor (F). They also added that similar linear plots would be obtained if the concentration of the pore fluid is plotted instead of the conductivity of pure electrolytes, based on the linear relationship between electrical conductivity of a pure electrolyte and its concentration. Formation Factor can be interpreted as the number of times the conductivity of the pure electrolyte is reduced due to the presence of solid particles in the electrolyte. They reported that for a given soil structure and unit weight, the formation factor can be determined just by the saturation of the soil with an electrolyte at different concentrations. It was found that the formation factor (F) shows little dependence on the amount of initial salt concentration of the soil after testing natural and washed silty clay compacted to same unit weight. Extending this observation to lime stabilized soils, it can be said that the electrical conductivity should increase with an increase in the amount of stabilizer (which would result in increased pore fluid concentration) and also raises the issue whether the formation factor of different soils with same amount of LKD should be the same irrespective of the pre-stabilization pore fluid chemistry.

Rinaldi and Cuestas (2001) found that samples with different pore fluids showed a linear variation in their electrical conductivity with an increase in concentration of the

pore fluid. However, the linear plots differed in their slopes, and the authors reported that this difference is due to the combined effect of ionic mobility, adsorption at particle surface and soil structure. Similarly, the conductivity of a soil stabilized with two different LKDs is expected to have different formation factors. To study the variation of formation factor with porosity, Rinaldi and Cuestas (2002) prepared natural and washed specimens saturated with sodium chloride at different densities and measured the conductivity. They found that the formation factor decreased with increasing porosity and that the relation can be modeled using Archies law shown by equation (2.18)

$$F = a \times n^{-m} \quad (2.18)$$

The present research study tried to test the appropriateness of extending these observations for lime stabilized soils and hence come up with a procedure to determine the amount of LKD present in a modified soil based on its electrical conductivity measurements.

The decrease in electrical conductivity is associated with a simultaneous increase in strength and hence there is a possibility of developing a correlation between strength and electrical conductivity. However, the correlation should also take into account the various other factors which affect the process. The apparent dielectric constant is expected to be a constant as it is relatively independent of pore fluid chemistry and hence can be used in determining the water content and dry density of a stabilized soil. The electrical conductivity of a lime modified soil is due to both the pore fluid and the free cations which result due to addition of lime. The amount of lime can be determined if the contribution of water content to the electrical conductivity can be separated from that of lime. Monitoring of lime stabilized samples for electrical conductivity on a long term would help in developing correlations between strength and conductivity.

CHAPTER 3. AUTOMATION OF GENERATION OF FAMILY OF CURVES

Compaction quality control of pavement subgrades and highway embankments is commonly done by use of a One-Point Test which is usually performed using a family of curves in accordance with AASHTO T 272. Determination of maximum dry unit weight (γ_{dmax}) and optimum moisture content (OMC) following the one-point method requires performing calculations and manually plotting the interpolated curve. It has been found that various state Departments of Transportation (DOTs) use family of curves that are state-specific rather than being site-specific, whereas the concept of One-Point Test is more reliable if the family of curves is site-specific. Developing site-specific family of curves is a time consuming process. An automatic method to generate a family of curves and to interpolate for a One-Point Test would result in quick, easy, and effective compaction control.

3.1. Mathematical Modeling of a Compaction Curve

To automate the generation of a family curves, a compaction curve should be initially modeled using a mathematical or an empirical model. Basheer (2001) used artificial neural networks and statistical regression analyses to empirically model a compaction curve based on measured soil properties and compaction energy. Neural networks require a large database of properties from a variety of soils. Others frequently use polynomial equations, but these equations are limited in their capacity to describe a compaction curve because the regression parameters change by up to three-orders of magnitude and the equations work well only over a limited moisture content range. A normal compaction curve runs parallel to the Zero-Air-Voids (ZAV) line at moisture contents well past the OMC and would never cross the ZAV line, whereas a polynomial fitting equation would violate this constraint. Equation (3.1), developed by Li and Sego (2000), overcomes the above mentioned shortcomings of polynomial equation modeling. It relates the dry unit weight of a soil with its moisture content using parameters G_s

(specific gravity of soil solids), γ_w (unit weight of water) and four coefficients (S_m , w_m , n , p) whose significance and method of determination were explained by Li and Sego (2000) and will be summarized subsequently.

$$\gamma_d(w) = \frac{G_s \gamma_w}{1 + \frac{w G_s}{S_m \left\{ 1 - \left(\frac{w_m - w}{w_m} \right)^{n+1} \left(\frac{w_m^n + p^n}{(w_m - w)^n + p^n} \right) \right\}}} \quad (3.1)$$

Equation (3.1) emerges from a basic understanding of the compaction behavior of fine grained soils. A complete compaction curve starts from a completely dry condition and ends well wet of the optimum water content whereas in normal practice, a compaction curve is restricted to only a compactable moisture content range. Li and Sego (2000) studied both the dry and wet conditions for a complete compaction curve. The dry unit weight of a fine grained soil in a complete compaction curve is nearly a constant from the totally dry state up to a moisture content threshold called the Compaction Sensitivity Threshold (CST). A plot between the degree of saturation (S) versus moisture content as shown in Figure 6 has a linear relationship up to the CST beyond which the degree of saturation increases rapidly until the moisture content reaches the optimum. The rate of increase in degree of saturation is very slow above optimum moisture content and ultimately reaches a constant. This maximum degree of saturation is denoted by S_m . The term w_m is the moisture content at which the soil attains this maximum degree of saturation S_m . The parameter n is called the shape factor which remains unchanged for a soil while compacting the soil using a given compaction method and it varies between 4 and 12 for natural soils. The parameter p corresponds to compactable moisture range which is the difference between the maximum and minimum moisture contents at which the soil is compactable and depends on the clay content of the soil.

Li and Sego (2000) introduced graphical methods to determine these four coefficients. These graphical methods are tedious as they require plotting degree of saturation against moisture content which requires additional calculations and geometric construction. An automatic method to generate a family of curves and to interpolate for a One-Point Test

was developed as part of this research. It facilitates quick, easy, and more accurate compaction control. The method also was extended for developing a family of curves for stabilized soil.

Figure 6. A Typical Plot between Degree of Saturation and Water Content

3.2. FAMCURVES

A Microsoft Excel program, FAMCURVES, which generates a family of curves and also interpolates for a One-Point Test to determine the optimum moisture content and maximum dry unit weight associated with this point was developed in this research study. The Li and Sego compaction curve equation was used to mathematically model the compaction curve. The value of γ_w is 62.4 lb/ft³ (9.80 kN/m³) and the value of G_s is assumed to be 2.72. The software requires the user to input the moisture contents and dry unit weights for various compaction curves in the family of curves. Macros use these data to determine the four coefficients for each compaction test data set. Instead of following the graphical methods proposed by Li and Sego, the “Solver” feature of Microsoft Excel was used to determine the four coefficients. Solver is a function of Excel which solves a

set of simultaneous equations within given constraints for the variables. It is sensitive to the initial values assigned to the variables. Simultaneous equations are formed with the four coefficients as the unknowns. The difference between input unit weights and unit weights calculated using Equation (3.1) form the simultaneous equations. Solver is used to minimize the sum of the squares of the difference between the input and calculated unit weights at various (input) moisture contents by changing the values of the four coefficients: S_m , w_m , n , and p . Considering the significance of the four coefficients, the following constraints for the four coefficients are applied:

- 1) The maximum degree of saturation, S_m , is usually never less than 80 percent and will never exceed 100 percent. Hence, S_m is constrained between the values 0.8 and 0.99.
- 2) The moisture content when soil attains a maximum degree of saturation, w_m , can never be less than the maximum moisture content for which the soil compaction data is input and is usually less than 40 percent. Hence, w_m is constrained to a maximum of 40 percent and a minimum of $(w_{max}+0.5)$ percent where w_{max} is the maximum moisture content of input data for the curve.
- 3) The coefficient n is constrained between the values proposed by Li and Sego, 4 and 12.
- 4) The compactable range of moisture contents, p , which is the difference between the maximum and minimum moisture contents at which the soil is compactable, typically varies between 3 percent and 15 percent. The coefficient p is constrained between these values.

The initial values of the four coefficients are critical in the process of using Solver. Choosing the initial values near the midpoint of the range to which they are constrained seems to work reasonably well. Initial values of 0.95 for S_m , 0.30 for w_m , 8.366 for n , and 0.09 for p were chosen for the examples herein. Once the four coefficients for a given compaction curve are determined, the equation is used to determine the dry unit weight of the soil at different water contents. The process is repeated for all of the given compaction curves. FAMCURVES displays a plot of dry unit weight versus water

content that shows the input data points and the generated compaction curves through them.

The program also can interpolate for the One-Point test for a given field moisture content and wet or dry unit weight. FAMCURVES determines the position of the given point with respect to the family of curves. The four coefficients for the compaction curve through the given point are determined through interpolation of the four coefficients of the two nearest curves to the point. Once the equation for the new compaction curve is established, FAMCURVES determines the OMC and γ_{dmax} using the “maximize” option in the Solver function. A new chart shows the input data point with the generated curve along with the family of curves. The gray curve in Figure 7 is interpolated from a single point having a moisture content of 15 percent and a dry unit weight of 105 lb/ft³ (16.82 kN/m³). It can be seen from Figure 7 that FAMCURVES interpolates a smooth compaction curve through the input point which fits very well on the family of curves.

Figure 7. Typical Example for family of curves Generation and One-Point Test Interpolation using FAMCURVES

FAMCURVES consists of an Excel Template file with “userforms” providing instructions and also enabling user to input data. The family of curves is presented on a chart in tab “Family A”; the one-point test on the newly generated family of curves is displayed on a chart in tab “Family B” and a different userform provides the output OMC and γ_{dmax} . FAMCURVES provides the flexibility of generating a family of curves with input data for a minimum of four curves to a maximum of seven curves. It also allows input of either four or five data points for each curve to cover the whole compaction curve. The macros contain error messages if inconsistent data are inserted or if the one-point data is not within the range of the family of curves.

To compare the accuracy of the four coefficients determined by FAMCURVES and the graphical method introduced by Li and Sego, compaction data of three soils was used to generate compaction curves using Equation (3.1) by determining the four coefficients by both the graphical method and by FAMCURVES. These curves are shown in Figure 8 where the bold data points correspond to experimental data, the gray curves are generated by curve fitting using the four coefficients determined by the graphical method and the black curves are generated by FAMCURVES. This figure indicates that the four coefficients determined by FAMCURVES result in a better curve fit when compared to the curve fit using the four coefficients derived by the graphical method. Equation (3.1) is very sensitive to the values of the four coefficients and precision up to four decimals is necessary for good curve fitting. Determination of the four coefficients by the graphical method lacks this precision that FAMCURVES provides through the use of sixteen significant digits for the coefficients.

Figure 8. Comparison of Curve fitting using Graphical Method and FAMCURVES.

3.3. Applications of FAMCURVES

3.3.1. Generation of a INDOT family of curves

The family of curves for natural soils, currently used by INDOT, was generated by FAMCURVES and is shown in Figure 9. Out of the eighteen curves present in the INDOT family of curves, only six curves (every third curve) were chosen. The triangle shaped data points are the input values scaled from INDOT's curves and the smooth curves are fitted by FAMCURVES using Equation (3.1).

Figure 9. INDOT family of curves Generation Using FAMCURVES

3.3.2. Estimation of Field Compaction Energy

FAMCURVES can be used to estimate the compaction energy applied in the field with respect to the compaction energy applied in the lab. If a given soil is compacted using different energies, like Under-compaction energy, Standard compaction energy and Modified Proctor energy, then a family of curves of the soil for various energies can be plotted. The data of a One-Point test performed in the field can be plotted on this family

of curves and the position of this point relative to the compaction curves will provide an idea of the relative magnitude of compaction energy applied in the field.

Data related to six soils tested with four different compaction energies in a recent research project were used to check the feasibility of this method. The four different compaction energies applied were Hand Compaction Energy, Under Compaction Energy, Standard Proctor Compaction Energy and Modified Proctor Compaction Energy. The soils varied from poorly graded sand to lean clays. Figure 10 shows the family of curves one of those soils, M3, whose engineering properties are provided in Table 1. Note that compaction by manual tamping with an aluminum rod does not provide a well defined curve and that the curves change character and position with increasing amounts of compaction energy.

Figure 10. Family of Compaction Curves with Different Compaction Energies Developed Using FAMCURVES.

Table 1. Engineering Properties of Soil M3

Engineering Property	Value
Particle Size Analysis	Sand-20%, Silt-55%, Clay-25%
USCS Classification	Lean Clay(CL)
AASHTO Classification	A-6
Plasticity Index	12
Compaction Characteristics	$\gamma_{dmax} = 120 \text{ lb/ft}^3$ OMC=12.5

3.3.3. Generation of Site Specific family of curves

It has been found that many DOTs use Families of Curves which are developed for soils representing the whole state. To check the appropriateness of this practice, the One-Point test for two natural soils, Salisbury Clay and Orchard Clay, from Indiana using AASHTO T 99 were performed. The engineering properties of these two soils are provided in Table 6. FAMCURVES was used to estimate the OMC and γ_{dmax} for these soils (See Figure 11) by using one data point from each curve (the chosen point is identified by the gray squares), which is within 80% of the optimum conditions on the dry side.

It was found that the OMC and γ_{dmax} of the interpolated curves differ from the actual compaction test results shown by the open-circle data points in Figure 11. The OMC and γ_{dmax} of the compaction curves of both soils from the actual compaction test results are to the right of the line of optima of the INDOT family of curves. The OMC of the interpolated curves differs by 2 percent and γ_{dmax} differs by about 3 lb/ft^3 (0.48 kN/m^3) from the experimental test data. It can be concluded from these observations that the concept of family of curves would be more reliable if site-specific Families of Curves are used instead of state-specific family of curves.

Figure 11. One-Point Test Using FAMCURVES vs. Actual Compaction Test Data

The application of FAMCURVES for generating a family of compaction curves for chemically modified soils was tested. These results will be discussed in subsequent chapters.

CHAPTER 4. EXPERIMENTAL PROGRAM AND RESULTS

The experimental program planned for this research study was aimed to address the following issues:

- Observe the field procedures followed to stabilize a soil
- Characterize the chemical composition of LKD
- Identify the reaction products between soil and LKD
- Study the changes in Atterberg limits of LKD stabilized soil
- Examine the effects of mellowing on compaction behavior of a stabilized soil
- Explore the possibility of developing a family of compaction curves for stabilized soils
- Study the behavior in electrical properties of stabilized soil and develop a method to estimate the amount of LKD in the modified soil
- Simulate field conditions in laboratory and study the potential of DCP and Two-Step TDR test for quality control of modified soils.
- Develop a quality control procedure for lime stabilized subgrades
- Draft guidelines

4.1. Subgrade Stabilization Site Field Trips

Field trips were necessary to make observations on field procedures that simulate laboratory procedures, and to come up with quality control procedures which are practical in the field. Trips were made to two different sites - Orchard sub-division, West Lafayette, Indiana on March 23rd, 2004 and the I-74 Batesville Rest Area, near Batesville, Indiana on October 13th, 2004. These trips enabled the research group to witness the methods followed and machines used in field to modify a plastic soil to a workable state. The natural soil was also collected during these field trips (Orchard clay and Batesville clay) which were used later for laboratory experiments. Additionally, field tests like TDR

and DCP were performed at different locations to test the possibility of developing them as quality control procedures and also to check the uniformity of mixing and improvement of properties based on the variability of test results with depth and from one location to another. Two-Step and One-Step TDR tests were performed during both the field trips. A DCP with an 8kg hammer was used to test the penetration resistance following ASTM D 6951-03, at two different locations of the Batesville Rest Area stabilization site. The number of blows required for a penetration of each 50mm was recorded.

Field stabilization is generally performed to a depth of 16 to 18 inches. The upper crust of soil is generally removed and the surface is prepared by rollers. The amount of LKD to be added is calculated in terms of pounds per cubic foot and is then spread on the prepared surface using a truck with a special LKD dispenser. It is clear from observations and this discussion that the addition of LKD is a crude process and is not uniform throughout the stabilized site. A tractor with special mixer blades then mixes the soil with the LKD to a depth of about 18 inches in two passes. A sheepsfoot roller is then used to compact the modified soil in one lift. The roller acts both as an impact and kneading compactor, attempting to produce a uniform mix of soil and LKD throughout the modification depth. A smooth roller is finally used to produce a smooth finish of the compacted modified soil.

Although care is taken to produce a uniform mix of LKD modified soil over the depth of modification, the final product is not uniform in terms of the compaction energy applied and the amount of LKD present over the length and depth of modified subgrade. Hence tests performed at a particular location over the length of the modified soil do not produce results which are representative of the entire modified subgrade. The results of the field tests conducted during these trips also support this notion.

4.2. Field Test Results

The DCP tests were performed approximately two hours after mixing at two locations in the east and west ramps during the field trip to Batesville Rest Area. The summary of the DCP test results are provided in Table 2. The penetration was done by recording the number of blows for each 50 mm increment of depth. This was converted

to penetration per blow by dividing 50 mm by the number of blows to advance the 50 mm. The penetration per blow is then multiplied with the hammer factor (which is equal to 1 for an 8 kg hammer) to determine the DCP index in the units of mm/blow. This DCP index is then converted into the corresponding CBR values based on the table provided in ASTM D 6951-03. From the table, we can observe that the tests at two different locations do not yield the same results. These differences can be attributed to the non-uniformity of mixing and unequal depths of modification.

Table 2. DCP Test Results for Batesville Rest Area Subgrade Stabilization

Location I			Location II		
Number of Blows per 50 mm	DCP Index mm/blow	CBR	Number of Blows per 50 mm	DCP Index mm/blow	CBR
3	17	13	3	17	13
4	13	17	2	25	8
4	13	17	2	25	8
2	25	8	2	25	8
3	17	13	2	25	8
6	9	32	2	25	8
3	17	13	1	50	4
4	13	17	1	50	4
5	10	20	1	50	4
4	13	17	2	25	8
3	17	13	2	25	8
4	13	17	3	17	13

Table 3 shows the results of both the Two-Step and One-Step TDR tests conducted at the same locations where DCP tests were performed roughly after two hours of mixing. It is not possible to determine the calibration constants for modified soil as the distribution of LKD in field is not uniform. Therefore, the water content and dry unit weight reported here are calculated using the calibration constants determined from laboratory compaction tests on Batesville clay without addition of LKD. From the table we observe that the field apparent dielectric constant measured using both Two-Step and One-Step method are very close. The water contents are also within $\pm 2\%$ of each other.

The oven dried water contents determined following ASTM D 2216, do not match well with the water contents found using both the TDR methods. However, it should be noted that there was a time lag between the collection of samples and oven drying them which may have led to evaporation and moreover the calibration constants are also not appropriate as they correspond to natural soil and not the modified soil.

Table 3. TDR Test Results for Batesville Rest Area Subgrade Stabilization

Two – Step TDR Method					One-Step TDR Method				Oven Dried
Location	K_{afield}	K_{amold}	γ_{dfield} (lb/ft ³)	w%	K_{afield}	EC_{bfield} (mS/m)	γ_{dfield} (lb/ft ³)	w%	w%
I	25.55	21.73	105	23.1	27.27	122.4	111	22.2	15.3
II	28.02	25.08	106	23.8	26.61	105.1	111	21.7	17.0

An ideal quality control test should give complete information regarding the amount of LKD, depth of modification, etc., at the location of testing. The DCP test can indirectly provide information on the depth of modification based on the penetration resistance; however it cannot provide information on the amount of stabilizer and water content and dry unit weight which are also key properties for a modified soil.

The One-Step TDR test requires only the length of probe to determine values of apparent dielectric constant and electrical conductivity. Research in this project, which will be discussed later, indicates that these two values can be correlated to the amount of LKD present in the soil. To estimate values of water content and dry density for soil from electromagnetic properties, six calibration constants are required. Determining the calibration factors for a modified subgrade is a challenge because they depend on the amount of LKD in the soil and field mixing of LKD with the soil is non-uniform.

The Two-Step TDR involves performing a test in the field and then performing another test on the soil removed from the field test location and compacted in a mold of known volume. It requires only two calibration constants and can provide information regarding the water content and dry unit weight of the soil. For natural soils these two constants do not vary significantly and can be assumed as $a = 1$ and $b = 8.5$. However, for

modified soils these values can vary over a wide range and a correlation should be developed between the amount of LKD and values for a and b . If the two calibration constants can be correlated to the amount of LKD, then a combined Two-Step and One-Step TDR test might be the solution of the problem. Amount of LKD can be initially estimated from the electrical conductivity and with the knowledge of the amount of LKD the two calibration constants can be estimated. These calibration constants can then be used to determine the water content and the dry unit weight of a soil using the Two-Step TDR test.

4.3. Materials

The research project used different locally obtained soils. Four natural clays (Salisbury clay, Orchard clay, Jasper clay, Batesville clay) and a mixture of Jasper clay and concrete sand (Jascrete) soil were used. Orchard clay was obtained during the field trip made to Orchard sub-division in West Lafayette. The chemical stabilizers used were lime kiln dust (LKD) and quicklime and were provided by Mount Carmel Sand and Gravel. LKD was used for majority of the experiments and quicklime was used to study the effects of mellowing on compaction behavior of soil. Two LKDs Buffington LKD (BLKD) and South Chicago LKD (CLKD) were used. Table 4 provides the chemical composition of quicklime and the LKDs used in this research project as provided by the supplier. It should be noted that the BLKD has more available lime than the CLKD. As evident from these reports, the chemical composition is not detailed and hence X-ray diffraction experiments were performed on both the LKDs in their natural and hydrated states. These experiments helped in characterizing the chemical composition and also to study the hydration products of LKD. Diffraction patterns were obtained using a PANalytical X'Pert PRO MPD x-ray diffraction system (PANalytical, Almelo, The Netherlands) equipped with a PW3050/60 θ - θ goniometer and a Co-target x-ray tube operated at 40 KeV and 35 mA. Incident beam optics consisted of an Fe beta filter, 0.04 radian Soller slit, and a programmable divergence slit and a beam mask set to illuminate a 10 x 10 mm sample area. A fixed, 1° anti-scatter slit was used at diffraction angles $<12^\circ$ 2 θ . The diffracted beam optics consisted of a programmable diffracted beam anti-scatter

slit, a 0.04 radian Soller slit, and a PW3015/20 X'Celerator detector configured for an active length of $2.12^\circ 2\theta$. Powder mounts were prepared in Al sample holders and scanned from 2 to $80^\circ 2\theta$ at 0.05° steps with 60 sec measurement time per step. The data were analyzed with the X'Pert High Score Plus software package (PANalytical, Almelo, The Netherlands) and were converted to a fixed 1° divergence slit prior to phase analysis and plotting. For testing hydrated samples, LKD was initially mixed with water and air-dried for two days. The samples were pulverized and powdered samples were prepared and tested in a similar way as those in the natural state.

Table 4. Chemical Composition of Stabilizers as Provided by Supplier

Quicklime		LKD	Buffington	South Chicago
Ingredient	% by weight	Characteristic	%Value	%Value
CaO	>84	Available Lime	32.2	11.3
Al ₂ O ₃	<1.5	Ca(OH) ₂ – Calculated	42.52	14.94
MgO	<15	Magnesium	1.65	27.73
Silica	<5	Hydroxide Equivalent	3.03	50.98
		Total equivalents as Ca(OH) ₂	30 – 45.55	65.92

Figure 12 shows the X-ray diffraction patterns of dry BLKD and Table 5 provides the list of possible chemical compounds present in the LKD based on the d-values of the diffraction peaks. From the table we observe that the LKD mainly consists of Ca in forms of CaCO₃, CaO, Ca(OH)₂. The oxide peaks prove the presence of quicklime; these peaks are sharp when compared to the peaks of the hydroxide. Figure 13 provides the diffraction patterns of both dry and hydrated forms of BLKD. From the figure we observe that intensity of the quicklime peaks decrease in hydrated samples while the peaks of Ca(OH)₂ increased at the same time proving the hydration of available quicklime. Similar figures for both dry and hydrated CLKD are provided in Appendix B.

Table 5. Possible Chemical Compounds in BLKD

Compound Name	Chemical Formula
Calcite	CaCO_3
Calcia	CaO
Dolomite	$\text{CaMg}(\text{CO}_3)_2$
Portlandite	$\text{Ca}(\text{OH})_2$
Silica	SiO_2
Periclase	MgO
Anhydrite	CaSO_4

Figure 12. X-ray Diffraction Pattern for Fresh BLKD

Figure 13. Comparison of XRD Patterns for Fresh and Hydrated BLKD

4.4. Tests on Natural Soils

Each soil was tested for basic index properties of grain size distribution following ASTM D 422 and AASHTO T 88, Atterberg limits following ASTM D 4318, compaction characteristics following ASTM D 698 and pH following ASTM D 4972. The optimum amount of stabilizer was determined following the standard ASTM D 6276 pH test using a Corning pH meter 44, a pH glass electrode and a calomel reference electrode. Salisbury clay was fractionated for x-ray diffraction analysis following the procedures described by Jackson (1969). Briefly, 5g of soil passing the standard sieve #10 (i.e. <2-mm) was Na saturated with pH 5 1M sodium acetate (NaOAc) buffer and organic matter was destroyed with 30% H₂O₂. The excess salt was removed by suspending the soil in deionized water, centrifuging and decanting the clear supernatant. The soil was suspended by sonicating using a 0.5" probe with a replaceable tip. The suspension was adjusted to pH 10 using dilute NaOH and fractionation proceeded using sieving (>50- μ m fraction), gravity sedimentation (50-20 μ m, 20-5 μ m, and 5-2 μ m fractions) and centrifugation (2-0.2 μ m, and <0.2 μ m). The <0.2 μ m fraction was flocculated with NaCl, then dialyzed against deionized water until free of Cl⁻. Fractions >5 μ m were air-dried, while fractions $\leq$ 5 μ m were flash frozen using liquid nitrogen, then freeze-dried. The dried fractions were stored in polypropylene bottles. Oriented mounts of the 5-2 μ m, and <0.2 μ m size fractions were prepared by sedimenting onto separate glass slides aliquots of Mg-saturated, glycerol- solvated material and K-saturated material. Diffraction patterns were obtained using CoK α radiation, and a Philips 3520 vertical diffractometer equipped with a fixed 1° divergence slit, 0.2mm receiving slit, incident and diffracted beam Soller slits, and a graphite, diffracted-beam monochromator. The samples were step-scanned from 2 to 35° 2 θ using a 0.5° 2 θ increment and 2-s count time per step. The Mg-glycerated slides were x-rayed at room temperature, while the K-saturated slides were x-rayed at room temperature and after heating to 300 and 550°C.

Table 6 summarizes the engineering properties of the various soils used in the study. From the table we find that the selected soils vary in their percent fines, plasticity index and compaction characteristics representing a wide range in type of soils tested. We

can also observe that the OMC and γ_{dmax} of a soil are related to its percentage fines. A high plastic soil like Salisbury clay and Jasper clay would tend to have a lower γ_{dmax} and a high OMC. On the other hand a sandy clay like Jascrete soil would exhibit a higher γ_{dmax} and a lower OMC. Orchard clay and Batesville clay lie midway between these extremes. Therefore the properties of the soils used for testing in this study covered the extremes in a family of compaction curves. Appendix A provides the relevant graphs for particle size distribution and compaction tests on various soils. From the table we also observe that the pH of all the soils used in the study is about 7 which is a typical value for glacial tills.

Table 7 provides the details of LMOs for both BLKD and CLKD of various soils determined in accordance with ASTM D 6276. Again from the table we observe that LMO for all soils with CLKD is consistently higher than that with BLKD which confirms that BLKD has greater amount of available lime than CLKD. Figure 14 and Figure 15 show the X-ray diffraction patterns of Salisbury clay for 2-5 μm and $<0.2\mu\text{m}$ particle size fractions Mg and K saturated slides.

Figure 14. X-ray Diffraction Patterns for 5-2 μm Fraction of Salisbury Clay

Figure 15. X-ray Diffraction Patterns for <0.2 μm Fraction of Salisbury Clay

Table 6. Engineering Properties of Various Soils Tested

Engineering Property	Salisbury Clay	Orchard Clay	Jasper Clay	Jascrete Soil	Batesville Clay
Particle Size Analysis	Sand-10%, Silt-48%, Clay-42%	Sand-28%, Silt-47%, Clay-25%	Sand-11%, Silt-60%, Clay-29%	Sand-50%, Silt-35%, Clay-15%	Sand-25%, Silt-52%, Clay-23%
USCS Classification	Lean Clay (CL)	Lean Clay (CL)	Lean Clay (CL)	Sandy Lean Clay (CL)	Lean Clay with Sand (CL)
AASHTO Classification	A-7-6	A-6	A-7-6	A-4	A-6
Liquid Limit	48	35	47	24	37
Plastic Limit	19	16	21	15	18
Plasticity Index	29	19	26	9	19
Compaction Characteristics	$\gamma_{dmax} = 106 \text{ lb/ft}^3$ OMC=19	$\gamma_{dmax} = 113 \text{ lb/ft}^3$ OMC=16.5	$\gamma_{dmax} = 103 \text{ lb/ft}^3$ OMC=20.5	$\gamma_{dmax} = 121.8 \text{ lb/ft}^3$ OMC=12.5	$\gamma_{dmax} = 115.8 \text{ lb/ft}^3$ OMC=15.5
Soil pH Distilled H ₂ O	7.76	7.74	7.01	7.00	
0.01M CaCl ₂	7.49	7.42	6.62	7.44	

Table 7. Lime Modification Optimums for Project Soils

Soil	BLKD	CLKD
Salisbury Clay		7%
Orchard Clay	4%	7%
Jasper Clay	5%	8%
Jascrete Clay	4%	6%

4.5. Tests on Modified Soils

4.5.1. Atterberg Limits of Modified Soil

The Atterberg limits of the LKD-modified soils were determined by slightly modifying the procedure specified in ASTM D 4318 for natural soils. The sample for Atterberg Limits is prepared in accordance with the Dry preparation method described in Section 10.2 of ASTM D 4318. About 200 grams of air dried soil is passed through a 425- μm (No.40) sieve and mixed with distilled water to form a paste with a consistency that would require about 25 to 35 blows of the liquid limit device to close the groove. The paste is mixed well to attain uniform water content throughout the sample. A small sample is retained to determine the water content of the paste following ASTM D 2216. The paste is then transferred to a porcelain dish and sealed air tight. The dish is allowed to temper in a humid room overnight. The following day, the water content is first determined and the soil in the porcelain dish is weighed. The mass of water is deducted from the mass of the paste to determine the weight of the solids. The required amount of LKD as a percent of the weight of the soil solids is then added to the paste and the mixture is mixed well using a spatula. Upon addition of LKD the paste becomes dry and hence more water is added to bring the sample to a consistency at which 15-35 blows can be obtained. Two methods Method-I and Method-II are followed from this stage.

4.5.1.1. Method I – Limits on Freshly-Mixed LKD Modified Soil

The liquid limit is found just after mixing the LKD with soil following the Method-A (Multipoint Liquid Limit) described in ASTM D 4318. Part of the sample is dried using an electric fan and tested for its plastic limit using the hand method described in ASTM D 4318. The remaining sample is collected into a porcelain dish and sealed air tight. The dish is allowed to cure in a humid room overnight to study the effects of LKD modification on soil with time. Liquid limit and plastic limit are determined the following day in a similar way as described earlier. Orchard clay and Jasper clay were tested following this method. Orchard clay was initially modified with LMO percent of BLKD and CLKD and tested two times (Trial I and Trial II) to check for repeatability. During Trial I, tests were conducted only just after mixing lime. However in trial II, tests were performed both just after mixing lime and also after 24 hours after mixing. Jasper clay was tested with LMO percent of BLKD.

Table 8 provides Atterberg limits test results for Orchard clay modified with LMO percent of BLKD and CLKD (4% and 7%, respectively) during trial 1 and trial 2 (replicate tests for repeatability as mentioned previously) and for Jasper clay modified with LMO percent of BLKD (5%) following Method I. Table 8 also provides the Atterberg limits of Orchard and Jasper clay in their natural state without any LKD. From the results of Trial 1 tests on Orchard clay with BLKD and CLKD presented in Table 8, we observe that, addition of LKD increased both the liquid limit and plastic limit of the soil resulting in a net increase of plasticity index with respect to that of natural soil. The liquid limit and plastic limit results of Trial 2 slightly varied from the Trial 1 results. These small variations increased the value of their difference (plasticity index) from Trial 1 to Trial 2. However, considering the experimental scatter associated in performing Atterberg Limit tests, the variations in liquid and plastic limit from Trial 1 to Trial 2 are reasonable.

Table 8. Atterberg Limits of LKD Modified Orchard Clay

Soil	Orchard Clay							Jasper Clay		
LKD	Natural	BLKD (4%)			CLKD (7%)			Natural	BLKD (5%)	
Sample		Trial1	Trial 2		Trial1	Trial 2			a *	b *
			a *	b *		a *	b *			
Liquid Limit	35	54	53	50	58	53	54	47	53	54
Plastic Limit	16	26	29	28	29	31	29	21	30	30
Plasticity Index	19	28	24	22	29	22	25	26	23	24

* a- just after mixing LKD, b- 24 hrs after mixing LKD

The results of the Atterberg limits tests performed on the mellowed sample (i.e. tested after 24 hours of mixing LKD with soil) are similar to the results obtained from samples tested just after mixing LKD. However, it should be noted that the plasticity index decreased in the case of BLKD and increased in case of CLKD. From the results of Atterberg limits tests performed on Jasper clay just after mixing LKD, we observe that the liquid and plastic limit increase resulting in a net decrease of plasticity index. Again, the test results of the mellowed sample are similar to results of tests performed just after mixing LKD. Based on the variation in the test results of Orchard clay and Jasper clay performed just after mixing and after 24 hours of mellowing, it can be concluded that mellowing of samples do not indeed bring major changes in the Atterberg limits of a soil.

4.5.1.2. Method II – Limits Tests on Mellowed LKD Modified Soil

The sample is air dried overnight on an acrylic plate after mixing with LKD. The air-dried sample is ground using a pestle and passed through the standard No.40 sieve. Water is added to this sample and mixed well to bring to a 15 blow consistency and then tested for liquid limit following Method –A (Multipoint Liquid limit) and plastic limit following hand method in compliance with ASTM D 4318. Again, Orchard clay and Jasper clay were both tested with their respective LMO percent of BLKD following this method.

The results of the Atterberg limit tests performed on Orchard clay and Jasper clay with LMO percent of BLKD following Method II are presented in Table 9.

Table 9. Summary of Atterberg Limits Tests following Method II

Soil	Orchard Clay		Jasper Clay	
LKD	Natural	4%BLKD	Natural	5%BLKD
Liquid Limit	35	42	47	45
Plastic Limit	16	22	21	25
Plasticity Index	19	20	26	20

Comparing the results of tests performed on unmellowed samples in Method I and mellowed samples in Method II, we observe that the increase in liquid limit and plastic limit is more significant in Method I. The plasticity index of Orchard clay increased and that of Jasper clay decreased in both cases. These differences can be attributed to the differences in the sample preparation procedure of Method I and Method II. The samples tested using Method II were allowed to mellow at room temperature of about 20°C which would promote cementation due to the formation of pozzolanic compounds. This cementation might have changed the particle size distribution rendering the soil less plastic. The samples tested just after mixing lime following Method I were not given sufficient time for the formation of pozzolanic compounds. Hence the increase in the liquid limit and plastic limit are more pronounced.

Although the mellowed samples prepared following Method I (during Trial 2) and Method II were tested after 24 hours of mixing LKD with soil, the results varied significantly. The samples prepared in Trial 2 of Method I were allowed to mellow in a humid room which is maintained at a temperature of 10°C. On the other hand, the samples prepared following Method II were mellowed at a room temperature of 20°C. Pozzolanic reactions are temperature dependent and hence the degree of cementation, due to the formation of pozzolanic compounds might have varied in samples mellowed following Method I and Method II. The samples prepared following Method I might have resulted in poor cementation as they were mellowed at a comparatively lower temperature. These differences in cementation and changes in particle size distribution are reflected in the results of their Atterberg limits.

4.5.1.3. Effects of Amount of LKD on Atterberg Limits

To study the effects of amount of LKD on the Atterberg limits of a soil, Orchard clay was modified with various percentages (1% to 6%) of BLKD and tested following Method I described earlier. A repeat test was performed using 4%LKD to substantiate the observation from the first set of tests. These tests were conducted just after mixing and not after 24 hours after mixing.

Figure 16 shows the Atterberg limit test results of Orchard clay with different amounts of BLKD. From the figure we see that with addition of LKD there is a sudden rise in the liquid limit and plastic limit of the soil and this trend continues with increasing amounts of LKD. The plasticity index follows the trend of liquid limit and plastic limit. However, with 4% BLKD, which is the LMO for Orchard clay with BLKD, there is a sudden drop in the plasticity index. The plasticity index rises again with addition of LKD beyond LMO. The results of the repeat test conducted with 4% BLKD are represented in Figure 16 by hollow data points. From the figure we observe that the plasticity index of the first test and second test matched very well, however, the values for liquid limit and plastic limit varied from the first test.

Although a drastic decrease in plasticity index is observed generally, Diamond and Kinter (1965) and Bell (1996) also found the increase of the plasticity index for lime modified soil. Based on the test results in this project, the addition of LKD to Orchard clay and Jasper clay increases both the liquid limit and plastic limit with respect to that of natural soil; but the plasticity index, which is the difference between the liquid limit and plastic limit increases for Orchard clay and decreases for Jasper clay. This occurs because the LKD affects the liquid limit and the plastic limit differently in these two soils.

Figure 16. Graphical Representation of Summary of Atterberg Limits Tests on Orchard Clay modified with Various Amounts of Buffington LKD

4.5.2. Compaction Tests

4.5.2.1. Effects of Mellowing

Salisbury was used to study the effects of mellowing on compaction characteristics of modified soil and also to monitor the changes in electrical conductivity with time. Two types of samples, unmellowed and mellowed, were prepared to study the effects of mellowing. For unmellowed samples air dried Salisbury clay passing through the standard No.4 sieve was hand-mixed with quicklime equivalent to the LMO at different water contents following the standard ASTM D 558-03. The samples were compacted immediately in a Standard Proctor Mold using standard energy and were monitored for their electrical conductivity and dielectric constant using PMTDR-SM Version 1.5 for 24 hours. For mellowed samples, air dried Salisbury clay passing through the standard No.4 sieve was hand-mixed with LMO amount of quicklime at different water contents and sealed in air tight plastic bags and retained in a humid room for 24 hours. The samples were then compacted the following day and then monitored for

electrical conductivity with the TDR apparatus as previously described. Furthermore, needle penetration resistance of the compacted samples was determined following ASTM D 1558 using a needle with a cross-sectional area of 1/40 square inch, to achieve a raw strength index of the soil. For both the unmellowed and mellowed samples, readings were taken just after compaction and also after 24 hours of compaction.

Figure 17 shows the effects of mellowing on compaction behavior of quicklime modified Salisbury clay. From the figure we observe that both OMC and γ_{dmax} of mellowed and unmellowed samples are lower than that of natural soil. The decrease in the density for the mellowed sample is significant and the compaction curve is almost flat. These results match well with the test results of Sweeney et al. (1988). However, the decrease in OMC is something which is not reported by past researchers. Subsequent tests and their results discussed in subsequent sections would explain this phenomenon better.

From TDR monitoring tests on quicklime-modified Salisbury clay, it was found that the electrical conductivity of both unmellowed and mellowed samples decreased with time for all water contents. Figure 18 compares the trend in electrical conductivity of 4% quicklime modified Salisbury clay with a pre-modification moisture content of about 20% for both unmellowed and mellowed samples. It can be seen from the graph that the unmellowed samples have a higher initial conductivity in comparison with the mellowed samples. The pozzolanic reactions form the pozzolanic compounds: calcium-silicate-hydrate (C-S-H) and calcium-aluminate-hydrate (C-A-H). Some pozzolanic reactions probably took place during the mellowing period in the mellowed samples, which would reduce the available free ions in the pore water and hence would result in a lower initial conductivity. Furthermore, it can be seen that the drop in the electrical conductivity of unmellowed sample over 24 hours is about twice the drop in electrical conductivity of mellowed samples 24 hours after compaction. It can be concluded that the rate of pozzolanic reactions (which would reduce the electrical conductivity) is more in the initial 24 hours after mixing lime and reduces with time. Similar results were obtained for samples compacted at various other moisture contents. These tests validated the observations of Yu and Drnevich and Boardman et al. (2001).

Figure 17. Effects of Mellowing on Compaction Characteristics of Salisbury Clay

Comparing the 24 hour electrical conductivity of the unmellowed sample with the initial conductivity of the mellowed sample, it can be observed that compaction results in increased rate of pozzolanic reactions. However, it should be noted that the unmellowed sample was not sealed during monitoring and hence some of the reduction in the electrical conductivity would be due to the evaporation of water. This was shown to be the case with the tests on modified Orchard clay sealed with wax which are presented subsequently. The tests on Salisbury clay helped in understanding the effects of mellowing and compaction on the rate of pozzolanic reactions in lime stabilized soils.

Figure 19 shows the trend in electrical conductivity with time for CLKD modified Salisbury clay at two different water contents. The trend in electrical conductivity with time for LKD modified soil is similar to the trend found in quicklime modified soil. Although the LKD modified samples were compacted at relatively low water contents (14% and 16%) their initial conductivity values are relatively higher in comparison with quicklime modified soils which were compacted at higher water content. These differences can be attributed to various other chemicals present in LKD besides CaO.

Figure 18. Trend in Electrical Conductivity with Time for both Mellowed and Unmellowed Samples of Quicklime (4%) Stabilized Salisbury Clay

Figure 19. Trend in Electrical Conductivity with Time for 4% CLKD Modified Unmellowed Salisbury Clay at Two Water Contents

Figure 20 is a plot between the electrical conductivity and the needle penetration resistance of quicklime-modified Salisbury clay for both unmellowed and mellowed samples. Both the penetration resistance and the electrical conductivity were measured just after compaction. From the plot we see that there is a linear relationship between needle penetration resistance and electrical conductivity. Considering needle penetration resistance as a strength index, the plot can be treated as a strength-conductivity correlation. However, the plot is soil specific and also dependent on time of testing after compaction as the conductivity decreases and needle penetration increases with time.

Figure 20. Plot between Needle Penetration Resistance and Electrical Conductivity for Mellowed and Unmellowed Samples of Quicklime Stabilized Salisbury Clay

4.5.2.2. Compaction Behavior of LKD Modified Soils

In the field, the mixing procedure of LKD and natural subgrade soil is not very uniform, and hence it is possible that the stabilized subgrade may contain varying amounts of stabilizer at different locations and at different depths at a given location. To account for this variability and also to study the compaction behavior of stabilized soil with different amounts of LKD, Orchard clay was modified and compacted with varying amounts of both BLKD and CLKD. BLKD was mixed in even numbered percentages i.e. 2%, 4%, 6%, 8% and CLKD was mixed in odd numbered percentages i.e. 3%, 5%, 7%, 9% . Air dried soil was mixed with different amounts of water and sealed in a plastic bag for overnight tempering in a humid room. The following day, the required amount of percent LKD calculated based on the weight of the solids was added, mixed for five minutes using a mechanical mixer shown in Figure 21 and then compacted. The electrical conductivity and the dielectric constant of the compacted sample were determined using the Purdue TDR apparatus just after compaction.

Figure 21. Mechanical Mixer used for Mixing LKD with Soil

Figure 22 shows the compaction behavior of Orchard clay modified with various amounts of BLKD. From the figure we can observe that, the addition of 2 and 4 percent of BLKD resulted in an increase in OMC and decrease in γ_{dmax} when compared to the natural soil. With addition of 6 percent BLKD, the OMC decreased back toward the OMC of the natural soil and the dry unit weight further decreased. Upon addition of 8

percent BLKD a significant additional decrease in OMC occurs and there is an increase in dry unit weight when compared to 6 percent BLKD. Tests conducted on Orchard clay modified with various amounts of CLKD yielded similar results. Figure 23 shows these results and it can be seen that the trend in compaction behavior is similar to the one shown in Figure 22. The OMC increased initially with the addition of 3% CLKD and decreased with addition of 5%, 7% and 9% of CLKD. The value of γ_{dmax} decreased with the addition 3% and 5% of CLKD in comparison to that of natural soil unit weight. Although γ_{dmax} with 7% CLKD was more than that of 5% CLKD it decreased again with 9% CLKD. It can be concluded from the observations made on Figure 22 and Figure 23 that compaction behavior of modified soils is complex and that using a family of curves for chemically modified soils may not be practical. However, if a family of curves is generated for modified soils, it should be LKD-specific because there is a difference in the compaction behavior of Orchard clay with the two LKDs. The behavior is dependent on the amount of LKD present in the soil and in the field this can vary with location and with depth due to non-uniform mixing.

Figure 22. Compaction Curves for Orchard Clay Modified with Various Amounts of Buffington LKD

Figure 23. Compaction Curves for Orchard Clay Modified with Various Amounts of South Chicago LKD

To check if the compaction behavior of other soils is similar to that observed in Orchard clay; Salisbury clay was modified with 2% and 4% CLKD; Jasper clay was modified with 4% and 8% of CLKD and 5% of BLKD; and Jascrete soil was modified with 4% BLKD and 6% CLKD. The three soils represent the three extremes of a family of curves, Jasper clay with a liquid limit of 47 is close to being a fat clay, Orchard clay represents typical lean clay and Jascrete soil represents sandy lean clay. Fat clays have a high OMC and low γ_{dmax} , sandy clays on the other hand have low OMC and high γ_{dmax} , and lean clays stand midway between fat clays and sandy clays. The samples were mixed with the mechanical mixer for five minutes and compacted in a similar fashion as described earlier for Orchard clay. The electrical conductivity and dielectric constant of all the LKD modified compacted samples were determined using Purdue TDR apparatus.

Tests on Salisbury clay with 2% and 4% CLKD helps to understand the compaction behavior of a soil with different amounts of LKD. Figure 24 shows the compaction behavior of Salisbury clay with and without LKD. The OMC decreased with small amounts of CLKD. This shows that the compaction behavior of a LKD-modified soil is soil specific. For the same amounts of LKD, the OMC increased for Orchard clay, whereas the OMC decreased for Salisbury clay. The percentage of fines is the primary difference between the two soils. This difference might have resulted in different compaction behavior. Upon addition of LKD, the grain size distribution of a clay soil changes to a coarser configuration of silty to sandy soil. This would lead to a decrease in the OMC. On the other hand addition of LKD to sandy lean clay would increase the amount of fines and hence would lead to an increase in the OMC. Figure 25 shows the compaction behavior of sandy lean clay Jascrete soil. It can be seen that addition of LKD resulted in an increase in OMC. Based on these observations on Salisbury and Jascrete clays, the compaction behavior of Orchard clay can be explained. Upon addition of small amounts of LKD to Orchard clay, the reactions between LKD and the fines are not complete. Therefore, the changes in grain size distribution are not well established and hence the OMC increases. With further addition of LKD the reactions between LKD and total fines are more complete and tend to govern the behavior resulting in a decrease in

OMC. The grain size distribution changes are pronounced with the addition of large amounts of LKD and soil behaves like silty or sandy clay.

Figure 24. Compaction Curves for Salisbury Clay Modified with Various Amounts of South Chicago LKD

The clay minerals present in Salisbury, Orchard, Jasper, and Jascrete clays can be assumed to be similar as they were obtained from the same city which would imply they have similar geological background. It should also be noted that for all the soils, the OMC of the modified soil with various amounts of LKD is within the range of ± 3 percentage points and the reduction in γ_{dmax} is about 4 lb/ft³ from that of the natural soil. However, estimating the magnitude of these variations with the knowledge of the amount of LKD in the soil is a problem which should be addressed after formulating a method that would provide information on the amount of LKD present in a soil.

Figure 25. Compaction Curves for Jascrete Soil Modified with Various Amounts of South Chicago LKD

4.5.2.3. Family of Curves for LKD Modified Soils

If it is assumed that, in the field, LMO amount of LKD was mixed uniformly throughout the length and depth of the modified subgrade, then it should be possible to generate a family of curves for modified soils. The compaction tests on Orchard clay; Jasper clay and Jascrete soil modified with LMO amount of BLKD and CLKD were used to develop family of curves.

Figure 26 and Figure 27 shows the family of curves for BLKD and CLKD, respectively. It can be seen that these family of curves do not look like the INDOT family of curves for natural soils. The curves are not distributed uniformly one below the other as in INDOT curves. From Figure 26 and Figure 27 it is clear that LKD specific family of compaction curves are necessary. Compaction curves of LKD-modified soil do not have a smooth fit and have distorted shapes. A family of curves made with Excel smooth fitting function may also overlap one over the other. Hence, FAMCURVES was used to generate these families of curves. Figure 28 and Figure 29 show these families of curves.

The data points in these graphs are experimental data and the curves are fitted using FAMCURVES. From the graphs we can see that FAMCURVES does a better job in fitting a smooth curve that passes through most of the points.

Figure 26. Family of Curves for Buffington LKD Modified Soils

Figure 27. Family of Curves for South Chicago LKD Modified Soils

Figure 28. Family of Curves using FAMCURVES for Buffington LKD Modified Soils

Figure 29. Family of Curves using FAMCURVES for South Chicago LKD Modified Soils

FAMCURVES was used to generate a family of curves for Orchard clay modified with different amounts of BLKD and CLKD. Figure 30 and Figure 31 show these curves and in both figures the data points correspond to the experimental data and the curves through these points were generated by FAMCURVES. From these figures we observe that FAMCURVES fits the curves through most of the experimental data points.

From Figure 30 and Figure 31 it is clear that, determining the amount of LKD at the test location is most important. The amount of LKD governs the OMC and γ_{dmax} , and also the strength of the soil. A test procedure which can provide information on the amount of LKD present in the soil is required.

Figure 30. Family of Compaction Curves for BLKD Modified Orchard Clay using FAMCURVES

Figure 31. Family of Compaction Curves for CLKD Modified Orchard Clay using FAMCURVES

4.5.2.4. Electrical Properties of LKD Modified Soils

As already mentioned the dielectric constant and electrical conductivity of all the modified soils were measured using Purdue TDR apparatus. These measurements were used for extending the observations of Rinaldi and Cuestas (2001) on Ohmic conductivity of compacted clays with electrolyte as pore fluid to LKD modified soils.

Figure 32. Linear Regressions between Electrical Conductivity Measured Immediately after Compaction and Water Content for BLKD Modified Orchard Clay

Figure 32 and Figure 33 shows the linear regressions of the plot between the electrical conductivity and water content of Orchard clay modified with various amounts of BLKD and CLKD and compacted with standard Proctor energy. From the figure it is clear that at any water content, the electrical conductivity increases with increasing amount of LKD. This observation was expected based on the results of Rinaldi and Cuestas (2002). In general the electrical conductivity of BLKD modified samples is more than CLKD modified samples. This difference can be attributed to the difference in the amount of free lime present in both the LKDs. The R^2 values of all the plots are high and the linear regressions passes through most of the data points. Figure 34 is a similar plot for both Jasper clay and Jascrete soil. The trends in this plot are similar to the trends in the plots for Orchard clay.

Figure 33. Linear Regressions between Electrical Conductivity Measured Immediately after Compaction and Water Content for CLKD Modified Orchard Clay

Figure 34. Linear Regressions between Electrical Conductivity Measured Immediately after Compaction and Water Content for CLKD Modified Jasper Clay and Jascrete Soil

As defined earlier, formation factor, F , is the inverse of the slope of the plot between electrical conductivity and concentration of a pore fluid at constant unit weight. For LKD-modified soil it is the inverse of the slope of the plot between electrical conductivity of the modified soil and the amount of LKD at constant water content. It is not possible to achieve the same unit weight with different amounts of LKD at same water content. Hence the water content should be fixed. However, the experimental data cannot be used to draw these plots as it is difficult to achieve the same water content for all the LKD modified samples. Hence the linear regression equations are used to determine the electrical conductivity of modified samples at various integral values of water content. Figure 35 is a typical plot between EC_b and %LKD for various water contents for BLKD modified Orchard clay. Again, the values of electrical conductivity are calculated using the linear equations developed in Figure 32. The inverse of the slope of the linear plots is the formation factor. Similar plots are developed for Orchard clay

modified with CLKD and for Jasper and Jascrete clay modified with both CLKD and BLKD. Figure 36 is a similar plot for Jasper clay.

Figure 35. Plot between EC_b Measured Immediately after Compaction vs. %LKD for BLKD-Modified Orchard Clay

Figure 36. Plot between EC_b Measured Immediately after Compaction vs. %LKD for BLKD-Modified Jasper Clay

Comparing Figure 35 and Figure 36 we see that, formation factor of different soils (Orchard and Jasper clay) with same amount of LKD at same water content are not the same. This observation is contradictory to results of Rinaldi and Cuestas (2002), who found that the formation factor of natural and washed samples at same porosity (i.e. with different initial salt concentration) were same. However, it should be noted that the measured electrical conductivity is affected by not only the pore fluid chemistry but also other factors such as percentage fines, clay minerals etc. It is known already that, Orchard clay and Jasper clay have different amount of fines although the clay minerals present can be assumed to be same.

Figure 37 shows the plot between electrical conductivity and %LKD for Orchard clay modified with CLKD at various water contents. Modification of Orchard clay with BLKD and CLKD would result in different pore fluid chemistry. Based on the results of Rinaldi and Cuestas (2002), the conductivity of a soil stabilized with two different LKDs is expected to have different formation factors. It can be seen that the slopes of the linear

regression in both the plots are different affirming the observations of Rinaldi and Cuestas (2002).

Figure 37. Plot between EC_b Measured Immediately after Compaction vs. %LKD for CLKD-Modified Orchard Clay

Figure 38 shows a plot between formation factor, F , and water content for various soils stabilized with BLKD and CLKD. Rinaldi and Cuestas (2002) found that the formation factor decreased with increasing porosity and that the relation can be modeled using Archies law ($F = a n^{-m}$). It can be seen from the fitting equations shown in Figure 38 that, the relation between formation factor and water content follows the Archie's law ($F = a w^{-m}$).

Figure 38. Plot between Formation Factor and Water Content for Project Soils

4.5.2.5. Long Term Monitoring of Modified Samples

A test program was planned to study the changes in the electrical properties of a modified soil with time over long term and also to develop a correlation between electrical conductivity and strength. Two samples of Orchard clay modified with LMO amount of BLKD (4%) at three different water contents, OMC and $\pm 2\%$ of OMC, were prepared. The first sample was used for monitoring the electrical properties with time and the second sample was used to test the penetration resistance using the apparatus described in ASTM C 403. The test with water content equal to OMC was repeated three

times (trial 1, 2 and 3). The trial 1 sample was not sealed and monitored for one week and trial 2 and 3 samples were sealed with wax and were monitored for 28 days. The conductivity was measured every hour for the first week and thereafter a reading was taken every day for 28 days. The second sample prepared in each trial was used to find the penetration resistance just after compaction, 24 hours after compaction, and one week after compaction. Only one trial was performed for tests with water contents $\pm 2\%$ OMC.

Figure 39 shows the comparison between the trends in electrical conductivity of three samples of Orchard clay modified with LMO amount of BLKD (4%) and compacted at a water content equivalent to its optimum. The three samples are labeled as Trial 1, 2, and 3. From the figure we observe that the rate of reduction in electrical conductivity of Trial 1 sample is rapid in comparison with Trial 2 and Trial 3 samples as it was not sealed with wax. This implies that the reduction in electrical conductivity of a LKD-modified sample is a combined effect of reduction in water content and formation of pozzolanic compounds. The results of the penetration resistance tests performed on Trial 2 and 3 samples are also shown with the penetration resistance given on the secondary Y-axis. From the plot we observe that the penetration resistance increases with time.

Figure 39. Long Term Monitoring Tests (Trial 1, 2 & 3) on Orchard Clay with OMC

Similar tests performed on Orchard clay with same amount of LKD at water contents $\pm 2\%$ of OMC yielded results which matched with previous tests. Figure 40 shows the plot between electrical conductivity and time for all the samples tested with 4% BLKD. We can observe from the figure that the initial electrical conductivity of the samples with water contents $\pm 2\%$ of OMC are relatively higher and lower than that of the electrical conductivity of the sample with OMC. However, the trend in the decrease in the electrical conductivity with time is similar to the trend observed in trial 2 and trial 3 samples.

Figure 40. Trend in Electrical Conductivity of 4% BLKD Modified Orchard Clay with Time

The effect of amount of LKD on the trend of electrical conductivity with time was then tested by performing similar tests on wax-sealed samples with 2% and 6% LKD at their corresponding OMCs. These results are shown along with the results of the tests with 4%LKD in Figure 41. From the figure it is clear that the rate of decrease in electrical conductivity is relatively high in sample with 6%LKD and relatively low in sample with 2% LKD in comparison with the samples with 4%LKD. The number of available ions

and the pozzolanic activity (i.e. the rate of formation of pozzolanic compounds) are dependent on the amount of LKD added. The higher the amount of LKD (6%LKD) the higher will be the number of available ions and the pozzolanic activity and hence higher will be the initial electrical conductivity. The lower initial electrical conductivity of sample with 2% LKD can be explained on similar lines. It is evident from the results presented so far that at any given time the electrical conductivity of a modified soil is dependent on both the water content and the amount of LKD present in it. The problem can be simplified by fixing one of the variables. This simplification was done by normalizing the electrical conductivity of a sample at any given time with its initial conductivity.

Figure 41. Trend in Electrical Conductivity of BLKD Modified Orchard Clay with Time

Figure 42 shows a plot between normalized electrical conductivity (EC_{btm}) and time, where normalized electrical conductivity (EC_{btm}) is defined as $EC_{btm} = \frac{EC_{bt0} - EC_{bt}}{EC_{bt0}}$ where EC_{bt0} is the initial electrical conductivity (at time $t=0$). Normalization of EC_b can

considered in two forms $EC_{bm} = \frac{EC_{bt0} - EC_{bt}}{EC_{bt0}}$ or $EC_{bm} = \frac{EC_{bt}}{EC_{bt0}}$. However the first form of normalization was preferred over the second as it provides the net change in the electrical conductivity at any given time in comparison with the initial electrical conductivity. Net change in electrical conductivity is in turn a measure of the net pozzolanic activity of a modified soil at any given time. The second form of normalization on the other hand compares the electrical conductivity at any given time with the initial electrical conductivity and does not reflect the net pozzolanic activity of the modified soil.

From the figure we observe that plots of samples with 4% LKD all follow the same curve. The plots for 2% and 6% LKD follow different paths. If further testing with other soils with same amount of LKD follow these curves, then at a given time with the value of normalized electrical conductivity the amount of LKD can be determined. Normalization removes the difference in initial conductivities which are related to the amount of fines and the presence of various clay minerals. The pozzolanic activity of a soil is a function of both percentage fines and amount of LKD. For the same amount of LKD, the pozzolanic activity of a soil with higher percentage of fines would be significant in comparison with a soil with very small amount of fines. Therefore, the curves shown in Figure 42 are soil specific and it is expected that behavior would change based on the amount of fines present in a soil. Further testing on a variety of soils like Jasper clay and Jascrete soil would help validate this hypothesis.

Figure 42. Trend in Normalized Electrical Conductivity of BLKD Modified Orchard Clay with Time

Figure 43. Plot between Penetration Resistance and Electrical Conductivity for LKD Modified Orchard Clay

The plot between the penetration resistance and the electrical conductivity for all the samples tested is shown in Figure 43. From the figure we observe that the curves between resistance and conductivity are linear for high conductivities (early after mixing and compaction) and then become flatter as the rate of increase in strength of the samples is high initially and then decreases with time. It can also be observed that for 4% BLKD-modified Orchard clay, at a given value of electrical conductivity the penetration resistance fall within a narrow range of values. In comparison, the penetration resistance of samples with 2% and 6% BLKD at a given value of electrical conductivity are lower and higher than that of sample with 4% LKD. With the knowledge of the amount of LKD determined following the procedure described previously, this graph works as a tool for estimating the penetration resistance of modified Orchard clay from the measured values of electrical conductivity. Again, the graph is specific to Orchard clay and cannot be applied to other soils. Further testing on other soils should check if a unique relationship exists between electrical conductivity and penetration resistance.

4.5.3. Pilot DCP Tests

Earlier researchers tried to perform field tests like DCP in the laboratory by compacting soil in a CBR mold. However, these tests do not simulate field conditions as a CBR mold provides lateral confinement to the soil which is not available in field. Moreover, the sample can be tested to only a limited depth in comparison to the field depth of stabilization. Hence, to simulate field boundary conditions it is necessary that the sample has sufficient depth and is not laterally confined. We studied the feasibility of testing a soil compacted in a mold with a diameter of 11 inches and a height of 9 inches (without the collar) as shown in Figure 44. The mold shown in Figure 44 has a volume of 0.5 ft^3 . Soil was compacted using standard Proctor compaction energy using a 5.5-lbf rammer and the soil was compacted in three lifts with 378 blows per lift.

Figure 44. 11" Compaction Mold

Each test required approximately 35 kilograms of soil and required a total of 1134 blows. Two pilot tests were performed on Orchard clay following this procedure. The first test was on natural soil without addition of LKD and the second test was performed on 4% BLKD modified Orchard clay. Both samples were tested only at single moisture content. In addition to a DCP test, Two-Step TDR test, One-Step TDR test and Needle Penetrometer tests also were performed.

The Two-Step TDR test was performed at the center of the compacted sample and three DCP tests were then performed at the midpoints of the three sides of the triangle

formed by the three outer spikes of TDR. Figure 41 shows the test layout of both TDR and DCP tests in the 11" mold. The cross-sectional area of the soil sample in the mold enabled driving the three spikes required to perform the TDR tests. As the density of the soil in the mold is already known, it was not necessary to excavate and compact the sample in a separate mold as mentioned in ASTM D 6780. Needle penetrometer tests were also performed near the DCP test locations. For the test on modified soil, for each lift, LKD was mixed with soil using a mechanical mixer.

Figure 45. Test Layout of an 11" Mold

DCP tests on Natural soil were performed at three different locations. For 4% LKD-modified soil, tests were performed both after one and three days after compaction. Table 10 shows the DCP resistance and corresponding CBR values estimated using the empirical equation provided in ASTM D 6951-03 for Orchard clay without LKD. According to ASTM D 6951-03, the estimated CBR is for insitu conditions, not for laboratory test conditions. From the table we observe that the penetration resistance is almost similar in all the cases.

Table 11 shows the DCP test results on the 4% LKD modified Orchard clay at the end of one and three days. From the table we can observe that the penetration resistance increases with time. This proves DCP to be a promising apparatus to test the penetration

resistance of a modified soil. As already mentioned, the test needs supplementary tests to obtain complete information on the performance of the modified soil. Factors like amount of LKD and water content and dry unit weight of the soil cannot be obtained from the test.

Table 10. DCP Test Results of Orchard Clay Compacted in 11" Mold

Trial 1				Trial 2				Trial 3			
No. of Blows	Penetration per Blow (mm)	DCP Index (mm/blow)	CBR	No. of Blows	Penetration per Blow (mm)	DCP Index (mm/blow)	CBR	No. of Blows	Penetration per Blow (mm)	DCP Index (mm/blow)	CBR
1	50.0	50.0	3.7	1	50.0	50.0	3.7	1	50	50	3.7
1	50.0	50.0	3.7	1	50.0	50.0	3.7	1	50	50	3.7
2	37.5	37.5	5.0	2	37.5	37.5	5.0	1	25	25	8.0
								1	50	50	5.0

Table 11. DCP Test Results on 4% BLKD-Modified Orchard Clay

Day 1				Day 3			
No. of Blows	Penetration between Readings (mm)	DCP Index (mm/blow)	CBR	No. of Blows	Penetration between Readings (mm)	DCP Index (mm/blow)	CBR
4	50	12.50	17	8	50	6.25	38
4	50	12.50	17	5	50	10.00	20
4	50	12.50	17	9	75	8.33	27
3	25	8.33	27				

Table 12 and Table 13 show the results of compaction and TDR tests performed on the Orchard clay with and without LKD in an 11" mold. The notation $\gamma_{t11''}$ and $\gamma_{d11''}$ refer to the total and dry unit weight of the soil in an 11" mold and γ_{dstd} refers to the dry unit weight as measured in a standard Proctor mold. The symbol γ_d refers to the dry unit weight as measured by the TDR apparatus following either One-Step or Two-Step methods. As the dielectric constant during the Two-Step TDR test was measured both using the field and mold screens, K_{afield} and K_{amold} are reported.

From the tables we observe that although the applied compaction energy was equivalent to standard Proctor energy, the resulting dry unit weight of the soil in 11" mold is lower than the standard Proctor density. The lateral confinement in standard Proctor mold results in a higher density. On the other hand, in an 11" mold the lateral confinement of the soil is closer to the situation for a soil compacted in field.

Table 12. TDR Test Results on Orchard Clay Compacted in 11" Mold

Measured		One-Step TDR		Two-Step TDR	
w%	17.6	w%	16	w%	18.73
$\gamma_{t11''}(\text{lb/ft}^3)$	123.6	K_a	18.79	$K_{a \text{ mold}}$	19.47
$\gamma_{d11''}(\text{lb/ft}^3)$	107.4	$EC_b(\text{mS/m})$	27.84	$K_{a \text{ field}}$	18.36
$\gamma_{dstd}(\text{lb/ft}^3)$	112.4	$\gamma_d(\text{lb/ft}^3)$	112	$\gamma_d(\text{lb/ft}^3)$	103.04

Table 13. TDR Results of 4% BLKD Modified Orchard Clay Compacted in 11" Mold

Measured		One-Step TDR		Two-Step TDR	
w%	17.4	w%	17.2	w%	16.7
$\gamma_{t11''}(\text{lb/ft}^3)$	122.0	K_a	28.1	$K_{a \text{ mold}}$	17.83
$\gamma_{d11''}(\text{lb/ft}^3)$	103.8	$EC_b(\text{mS/m})$	88.9	$K_{a \text{ field}}$	21.54
$\gamma_{dstd}(\text{lb/ft}^3)$	111.6	$\gamma_d(\text{lb/ft}^3)$	133	$\gamma_d(\text{lb/ft}^3)$	108.8

The water content and dry density results from Two-Step TDR test for both cases are close to the measured values. It should be noted here that the calibration constants (a and b) used in the 4% LKD case for determination of water content and dry unit weight were determined from the compaction tests performed of Orchard clay with 4% BLKD. The effects of steel mold forming a second coaxial cable on the measured values of

dielectric constant are not considered and should be resolved by further testing. Assuming that the effects of steel mold on the measured dielectric constant is negligible, it can be concluded from these test results that, the Two-Step TDR test is a reliable method to determine moisture content and unit weight of natural soils. Its application for LKD modified soils is warranted only if a reliable estimate of calibration constants a and b can be made.

The water content measurements as estimated by the One-Step method are reasonable in comparison with the measured values. However, the dry unit weight as estimated by the One-Step TDR method for both the natural and 4% LKD cases are not appropriate. The erroneous results might be due to the formation of two coaxial cables – one by the 11" mold and the other by three spikes. Without proper knowledge of the six calibration constants, One-Step TDR method has difficulty accurately determining the dry unit weight of a LKD modified soil. However, the test can provide information on electrical conductivity and dielectric constant, which based on the findings of this research are very valuable in characterizing a LKD modified soil.

CHAPTER 5. CONCLUSIONS AND FUTURE RESEARCH NEEDS

The research project characterized LKD as a chemical stabilizer and studied the behavior of LKD-modified soils using various testing methods. Characterization of LKD was based on the X-ray diffraction experiments. The basic engineering properties like particle size distribution, Atterberg limits, pH, and compaction characteristics of all the soils used in the research were determined following ASTM standards. The Atterberg limits, compaction behavior and the variation in electrical properties of LKD-modified soils were extensively studied. The interpretation of these test results was made in the previous chapter. This chapter will highlight some conclusions which can be deduced based on the test results and will propose the needs and guidelines for future research.

5.1. Conclusions

An automated method to generate a family of compaction curves was developed in the form of the program FAMCURVES. FAMCURVES has a user-friendly interface on a Microsoft Excel platform. It can be used to generate families of curves and interpolate for a one-point test in field compaction control. The program has additional applications like the generation of a family of curves for estimating the compaction energy applied to a given soil.

Based on the observations made on lime modification of subgrades during field trip, it can be concluded that amount of lime applied, thoroughness of mixing, and amount of compaction in the field are not as controlled as in a laboratory. The method of spreading, mixing and compaction in field, although efficient, does not produce a totally uniform subgrade. The amount of LKD and temperature are other factors which cannot be controlled effectively in field. Simulating field conditions in lab therefore is quite challenging.

From the results of the DCP tests performed during the field trip to Batesville Rest Area and the pilot tests in 11" mold performed in the laboratory, the DCP test can be considered a candidate test for quality control of LKD-modified subgrades. Other, more automated penetration tests also are candidates. However, they should be supplemented with other tests that can provide information on the amount of LKD present in a soil and the depth and uniformity of mixing. With the knowledge of correct values of a and b , Two-Step TDR test can be used for the determination of water content and dry unit weight of modified soil.

The X-ray diffraction tests on both the LKDs justified their use for chemical modification of subgrades. Due to the differences in the amount of available lime in both LKDs, differing amounts of each would be required to modify a given soil in the field. Assuming that the every batch of LKD from both the plants is consistent in chemical composition, a greater amount of CLKD is required to bring about the same changes in a soil. Contractors in the field should be aware of this fact in order to achieve desired results.

Based on the results of the Atterberg limit tests performed on Orchard clay and Jasper clay, it can be concluded that Atterberg limits of a LKD-modified soil are a function of number of factors that include soil type, specimen preparation method, mellowing time, and amount and type of LKD. Both the liquid limit and plastic limit change upon addition of LKD and their difference, the plasticity index, can either increase or decrease.

Mellowing of modified soils resulted in a lower unit weight and lower initial electrical conductivity. The shape of the compaction curve of an LKD-modified soil is generally distorted in comparison with that of the same soil in natural state. The OMC and γ_{dmax} of a LKD-modified soil vary with the type and amount of LKD and also the amount of fines present in a soil. Generating a useable family of curves for chemically modified soil is therefore not possible. Moreover, moisture content and unit weight criteria for quality control are not sufficient and should be supplemented by other types of tests that indicate shear strength and amount of LKD.

The electrical conductivity of a LKD-modified soil is dependent on the water content and the amount of LKD present in the soil. The observations of Rinaldi and Ceustas (2001) on the electrical properties of compacted clay with various pore fluids were extended to LKD-modified soils. It was found that soils with same amount of LKD do not have same formation factors and that the relation between formation factor and water content follow Archie's law ($F = a w^{-m}$).

The plot between normalized electrical conductivity and time from the results of the long term monitoring tests were found to be consistent and instructive. The variation in normalized electrical conductivity with time for a combination of LKD and soil at any water content was found to be unique. A plot of normalized electrical conductivity can be used to determine the amount of LKD present in LKD-modified Orchard clay at any time. This situation should apply to lime and LKD modified clay soils in general.

The plot between penetration resistance and electrical conductivity identified electrical conductivity to be a good indirect indicator of the strength of a modified soil. However, further testing is required to define field testing procedures.

5.2. Recommendations & Future Research Needs

Water content, dry unit weight, shear strength, amount of LKD, and depth and uniformity of mixing are the parameters which are necessary for characterizing a LKD-modified subgrade. An ideal quality control method for characterizing modified subgrades should be quick and easy to perform and at the same time should provide information related to the aforementioned factors. This research project tested the use of the moisture content, dry unit weight, TDR-measured parameters, and the DCP test for quality control of LKD-modified subgrades. None of the tests alone is sufficient for quality control. Moisture content and dry unit weight, which are used in conventional soils are not good indicators for LKD-modified soils because dry unit weight decreases with good quality modification that provides significantly improved properties. The optimum water content of modified soils is strongly affected by the amount of LKD applied and first increases and then decreases with increasing LKD. Preliminary test

results show that further research is necessary to come up with a complete quality control procedure. Following are some recommendations and needs for future research

1. Develop field procedures for using the DCP (or other penetration type tests) in conjunction with TDR tests to characterize modified soil;
2. Verify the unique relationship between normalized electrical conductivity and time for a wider combination of soils and LKD;
3. The long term monitoring tests performed so far were using BLKD. The variation in the electrical conductivity of samples modified using CLKD and other sources of LKD and lime should be tested as a part of further research;
4. Study the effects of temperature on the chemical changes and the measured electrical conductivity of a LKD-modified soil;
5. Although the tests in 11" mold are very tedious they allow simulating field boundary conditions and performing multiple tests like DCP and TDR at various time intervals after compaction. Automation of the test might help in developing correlations for a variety of soils between electrical conductivity and DCP penetration resistance similar to the correlations developed in this research.
6. The reactions between lime and soil and the measured electrical conductivity of a soil are temperature dependent. Field temperatures can vary over a large range of values. The effects of temperature are not studied as a part of this research. Future research should study the variation in electrical conductivity of samples compacted and cured at various temperatures which are possible in field.
7. Continue the use of X-ray diffraction and scanning electron microscopy LKD-modified soils to investigate the formation of pozzolanic compounds;
8. Establish for a variety of modified soils the relationship between DCP and TDR measured parameters with shear strength, stiffness, and hydraulic conductivity of modified soils.
9. Test, research and develop pick up truck mounted mechanical DCP devices to improve the speed and consistency of test results.

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APPENDICES

Appendix A: Particle Size Distribution of Project Soils

This chapter presents the particle size distribution of all the soils used in the project – Salisbury clay, Orchard clay, Jasper clay and Jascrete soil.

Figure 46. Particle Size Distribution of Salisbury Clay

Figure 47. Particle Size Distribution of Orchard Clay

Figure 48. Particle Size Distribution of Jasper Clay

Figure 49. Particle Size Distribution of Jascrete Soil

Figure 50. Particle Size Distribution of Batesville Clay

Appendix B: Chemical Composition and X-Ray Diffraction Patterns of CLKD

Table 14. Possible Chemical Compounds in CLKD

Compound Name	Chemical Formula
Calcite	CaCO_3
Calcia	CaO
Dolomite	$\text{CaMg}(\text{CO}_3)_2$
Portlandite	$\text{Ca}(\text{OH})_2$
Silica	SiO_2
Periclase	MgO
Anhydrite	CaSO_4

Figure 51. X-Ray Diffraction Pattern of Fresh CLKD

Figure 52. X-ray Diffraction patterns of Fresh and Hydrated CLKD